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# Dark Energy Survey Year 1 Results: redshift distributions of the weak-lensing source galaxies

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## ABSTRACT

We describe the derivation and validation of redshift distribution estimates and their uncertainties for the populations of galaxies used as weak-lensing sources in the Dark Energy Survey (DES) Year 1 cosmological analyses. The Bayesian Photometric Redshift (BPZ) code is used to assign galaxies to four redshift bins between  $z \approx 0.2$  and  $\approx 1.3$ , and to produce initial estimates

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of the lensing-weighted redshift distributions  $n_{\text{pz}}^i(z) \propto dn^i/dz$  for members of bin  $i$ . Accurate determination of cosmological parameters depends critically on knowledge of  $n^i$ , but is insensitive to bin assignments or redshift errors for individual galaxies. The cosmological analyses allow for shifts  $n^i(z) = n_{\text{pz}}^i(z - \Delta z^i)$  to correct the mean redshift of  $n^i(z)$  for biases in  $n_{\text{pz}}^i$ . The  $\Delta z^i$  are constrained by comparison of independently estimated 30-band photometric redshifts of galaxies in the Cosmic Evolution Survey (COSMOS) field to BPZ estimates made from the DES *griz* fluxes, for a sample matched in fluxes, pre-seeing size, and lensing weight to the DES weak-lensing sources. In companion papers, the  $\Delta z^i$  of the three lowest redshift bins are further constrained by the angular clustering of the source galaxies around red galaxies with secure photometric redshifts at  $0.15 < z < 0.9$ . This paper details the BPZ and COSMOS procedures, and demonstrates that the cosmological inference is insensitive to details of the  $n^i(z)$  beyond the choice of  $\Delta z^i$ . The clustering and COSMOS validation methods produce consistent estimates of  $\Delta z^i$  in the bins where both can be applied, with combined uncertainties of  $\sigma_{\Delta z^i} = 0.015, 0.013, 0.011$ , and  $0.022$  in the four bins. Repeating the photo- $z$  procedure instead using the Directional Neighbourhood Fitting algorithm, or using the  $n^i(z)$  estimated from the matched sample in COSMOS, yields no discernible difference in cosmological inferences.

**Key words:** methods: data analysis – catalogues – surveys.

## 1 INTRODUCTION

The Dark Energy Survey (DES) Year 1 (Y1) data places strong constraints on cosmological parameters (DES Collaboration et al. 2017) by comparing theoretical models to measurements of (1) the autocorrelation of the positions of luminous red galaxies at  $0.15 < z < 0.9$  (Elvin-Poole et al. 2017) selected by the REDMAGIC algorithm (Rozo et al. 2016); (2) the cross-correlations among weak-lensing (WL) shear fields (Troxel et al. 2017) inferred from the measured shapes of ‘source’ galaxies divided into four redshift bins (Zuntz et al. 2017); and (3) the cross-correlations of source galaxy shapes around the REDMAGIC (‘lens’) galaxy positions (Prat et al. 2017). There are 650 000 galaxies in the REDMAGIC catalogue covering the  $1321 \text{ deg}^2$  DES Y1 analysis area, and 26 million sources in the primary WL catalogue. For both the lens and the source populations, we rely on DES photometry in the *griz* bands<sup>1</sup> to assign galaxies to a redshift bin  $i$ . Then, we must determine the normalized distribution  $n^i(z)$  of galaxies in each bin. This paper describes how the binning and  $n^i(z)$  determination are done for the source galaxies. These redshift distributions are fundamental to the theoretical predictions of the observable lensing signals. Uncertainties in the  $n^i(z)$  must be propagated into the cosmological inferences, and should be small enough that induced uncertainties are subdominant to other experimental uncertainties. The bin assignments of the source galaxies can induce selection biases on the shear measurement, so we further discuss in this paper how this selection bias is estimated for our primary shear measurement pipeline. The assignment of redshifts to the lens galaxies, and validation of the resultant lens  $n^i(z)$ ’s, are described elsewhere (Rozo et al. 2016; Elvin-Poole et al. 2017; Cawthon et al. in preparation).

A multitude of techniques have been developed for estimation of redshifts from broad-band fluxes (e.g. Arnouts et al. 1999; Benítez 2000; Bender et al. 2001; Collister & Lahav 2004; Feldmann et al. 2006; Ilbert et al. 2006; Hildebrandt et al. 2010; Carrasco Kind & Brunner 2013; Sánchez et al. 2014; Rau et al. 2015; Hoyle 2016; Sadeh, Abdalla & Lahav 2016; De Vicente, Sanchez & Sevilla-

Noarbe 2016). These vary in their statistical methodologies and in their relative reliance on physically motivated assumptions versus empirical ‘training’ data. The DES Y1 analyses begin with a photometric redshift algorithm that produces both a point estimate – used for bin assignment – and an estimate  $p^{\text{PZ}}(z)$  of the posterior probability of the redshift of a galaxy given its fluxes – used for construction of the bins’  $n^i(z)$ .

The key challenge to use of photo- $z$ ’s in cosmological inference is the *validation* of the  $n^i(z)$ , i.e. the assignment of meaningful error distributions to them. The most straightforward method, ‘direct’ spectroscopic validation, is to obtain reliable spectroscopic redshifts for a representative subsample of the sources in each bin. Most previous efforts at constraining redshift distributions for cosmic shear analyses used spectroscopic redshifts either as the primary validation method, or to derive the redshift distribution itself (Benjamin et al. 2013; Jee et al. 2013; Schmidt & Thorman 2013; Bonnett et al. 2016; Hildebrandt et al. 2017). Direct spectroscopic validation cannot, however, currently reach the desired accuracy for deep and wide surveys like the Y1 DES, because the completeness of existing spectroscopic surveys is low at the faint end of the DES source-galaxy distribution (Bonnett et al. 2016; Gruen & Brimiouille 2017), and strongly dependent on quantities not observed by DES (Hartley et al., in preparation). In detail, the larger area of the DES Y1 analysis compared to other WL surveys, including the DES Science Verification (SV) analysis (Bonnett et al. 2016), reduces the statistical uncertainties such that the systematic uncertainties from performing a direct calibration using spectra become dominant.

The validation for DES Y1 source galaxies therefore uses high-precision redshift estimates from 30-band photometry of the COSMOS survey field (Laigle et al. 2016), which are essentially complete over the colour-magnitude space of the Y1 source catalogue, in a more sophisticated version of the approach used in Bonnett et al. (2016). This direct approach is then combined with constraints on  $n^i(z)$  derived from cross-correlation of the source galaxy positions with the REDMAGIC galaxy positions as an independent method of photometric redshift validation (see e.g. Newman 2008 for an introduction to the method and Cawthon et al. in preparation; Davis et al. 2017; Gatti et al. 2017 for the application to DES Y1). The cross-correlation redshift technique will be referred to as ‘WZ,’ and the validation based on the 30-band COSMOS photometric red-

<sup>1</sup>While there is Y- band data available, due to its lower depth, strong wavelength overlap with  $z$ , and incomplete coverage, we did not use it for photo- $z$  estimation.

shifts will be referred to as ‘COSMOS,’ and the estimates returned from photo- $z$  algorithms run on the DES *griz* photometry will be marked as ‘PZ.’ Indeed, we suggest reading this paper in conjunction with those of Gatti et al. (2017) and Davis et al. (2017), which are dedicated to documenting the WZ procedure in greater detail. We also summarize the salient parts of these papers throughout this manuscript and discuss the issue of the failure of the REDMAGIC sample to span the full redshift range of the Y1 lensing sources, which leaves gaps in our knowledge of  $n^i$  derived from WZ.

For the analysis in this work, the cosmological inference will assume that the redshift distribution in bin  $i$  is given by

$$n^i(z) = n_{\text{PZ}}^i(z - \Delta z^i), \quad (1)$$

where  $n_{\text{PZ}}^i(z)$  is the distribution returned from the photometric redshift code using DES *griz* photometry, and  $\Delta z^i$  is a free parameter to correct any errors resembling a shift of the photo- $z$  result (see also Jee et al. 2013; Bonnett et al. 2016). The cosmological inference code is given a probability distribution for  $\Delta z^i$ , which is the normalized product of the probabilities returned by the WZ and COSMOS analyses. It is apparent that equation (1) essentially allows the mean source redshift returned by the PZ method to be altered by the information provided by the COSMOS and WZ validation procedures, but the shape of  $n^i(z)$  about its mean retains its PZ determination.

This paper begins in Section 2 with a description of the input catalogues, real and simulated, for the source redshift inferences and validation. Section 3 describes the photometric redshift algorithms applied to the DES broad-band fluxes. We describe the direct COSMOS validation method in Section 4. The derivation of WZ constraints from angular clustering is the subject of Cawthon et al. (in preparation), Davis et al. (2017), and Gatti et al. (2017). In Section 5, we combine these WZ constraints on  $\Delta z^i$  with those from COSMOS to yield the final constraints. We describe the use of these redshift constraints as priors for the DES Y1 cosmological inference, including an examination of the impact of the assumption in equation (1) and other known shortcomings in our process, in Section 6 and conclude in Section 7.

Aspects of the  $n^i(z)$  estimation and validation procedure not immediately required for Y1 lensing analyses will be described in Hoyle et al. (in preparation) and Rau et al. (in preparation).

## 2 INPUT CATALOGUES

Estimation and validation of the binning and  $n^i(z)$  functions for the Y1 source galaxies require input photometry for these galaxies of course, but also Dark Energy Camera (DECam, Flaugher et al. 2015) data (Sánchez et al. 2014) and external data on the COSMOS field used for validation. Finally, our validation uses simulations of the COSMOS catalogue to estimate sample-variance uncertainties induced by the small sky area of this field. Fluxes and photo- $z$ ’s must be estimated for these simulated galaxies.

### 2.1 Lensing sources

The set of galaxies for which bin assignments and  $n^i(z)$  estimates are desired are the WL sources defined in the Y1 shear catalogues documented in Zuntz et al. (2017). The primary shear catalogue for DES Y1 is produced by the METACALIBRATION algorithm (Huff & Mandelbaum 2017; Sheldon & Huff 2017), and a secondary catalogue using IM3SHAPE (Zuntz et al. 2013) is used as a cross-check. For both shear catalogues, we use a common photo- $z$  catalogue based on our best measurements of fluxes (the ‘MOF’ catalogue described below) to estimate the  $n^i(z)$  of each bin (see Section 3.3 for

details). These  $n^i(z)$  differ, however, because METACALIBRATION and IM3SHAPE implement distinct selection criteria and bin assignments.

The starting point for either shear catalogue is the Y1 GOLD catalogue of sources reliably detected on the sum of the  $r$ -,  $i$ -, and  $z$ -band DES images (Drlica-Wagner et al. 2017). Detection and initial photometry are conducted by the SExtractor software (Bertin & Arnouts 1996). Photometric zero-points are assigned to each DES exposure using nightly solutions for zero-points and extinction coefficients derived from standard-star exposures. Exposures from non-photometric nights are adjusted to match those taken in photometric conditions.

As detailed in Drlica-Wagner et al. (2017), the photometric calibration is brought to greater colour uniformity and adjusted for Galactic extinction by stellar locus regression (SLR, Ivezić et al. 2004; MacDonald et al. 2004; High et al. 2009): the  $i$ -band fluxes are adjusted according to the Galactic extinction implied by the Schlegel, Finkbeiner & Davis (1998) dust map with the O’Donnell (1994) extinction law. Then, the zero-points of other bands are adjusted to force the stellar colour–colour loci to a common template.

Fluxes used as input to the photo- $z$  programs for both shear catalogues are derived using NGMIX<sup>2</sup> (Sheldon 2014; Jarvis et al. 2016), which fits a model to the pixel values of each galaxy in the GOLD catalogue. The NGMIX code fits a highly constrained exponential+deVaucouleurs model to each galaxy: the model is convolved with each exposure’s point spread function (PSF) and compared to pixels from all individual exposures covering the source. The fitting is multi-epoch and multiband: pixels of all exposures in all bands are fit simultaneously, assuming common galaxy shape for all bands and a single free flux per band. The fitting is also multi-object: groups of overlapping galaxy images are fit in iterative fashion, with each fit to a given galaxy subtracting the current estimate of flux from neighbours. These ‘multi-object fitting’ (MOF) fluxes are used as input to photo- $z$  estimators for IM3SHAPE and METACALIBRATION catalogue member galaxies (although we use a different flux measurement for bin assignment in the case of METACALIBRATION, see below).

The photo- $z$  assigned to a galaxy depends on its measured multi-band fluxes, which will vary if there is shear applied to the galaxy. So the photo- $z$  bin to which a galaxy is assigned might depend on how much it is sheared, leading to a potential selection bias. For IM3SHAPE, we have confirmed, using realistic image simulations, that these selection biases are small (at or below the one per cent level), and have added a term in the systematic uncertainty of the shear calibration to account for them (cf. section 7.6.2 of Zuntz et al. 2017, called *variation of morphology* there). METACALIBRATION, on the contrary, can estimate and correct selection biases on the WL shear inference by producing and remeasuring four artificially sheared renditions of each target galaxy (by  $\gamma_1 = \pm 0.01$  and  $\gamma_2 = \pm 0.01$ , where  $\gamma_{1,2}$  are the two components of the shear). The selection bias correction in METACALIBRATION requires knowing whether each source would have been selected and placed in the same bin if it had been sheared. It is thus necessary for us to run the photo- $z$  estimation software not only on the original fluxes, but also on fluxes measured for each of the four artificially sheared renditions of each galaxy. The latter are not available from the MOF pipeline.

For the METACALIBRATION catalogue, we therefore produce an additional set of photo- $z$  estimates based on a different flux measurement made with the METACALIBRATION pipeline. This measurement makes use of a simplified version of the NGMIX procedure described above: the model fit to the galaxies is a PSF-convolved Gaussian, rather

<sup>2</sup><https://github.com/esheldon/ngmix>



than a sum of exponential and deVaucouleurs components. These ‘Metacal’ fluxes do not subtract neighbours’ flux. In addition to fluxes, METACALIBRATION also measures pre-seeing galaxy sizes and galaxy shapes (Zuntz et al. 2017).

There are thus six distinct photo- $z$ ’s for the WL source galaxies: one produced using the MOF fluxes for galaxies in either of the IM3SHAPE or METACALIBRATION shape catalogues; one produced using Metacal fluxes of the as-observed sources in the METACALIBRATION shape catalogue; and four produced using Metacal fluxes of the four artificially sheared renditions of the sources in the METACALIBRATION catalogue.

## 2.2 COSMOS catalogue and DES *griz*

### 2.2.1 DES fluxes

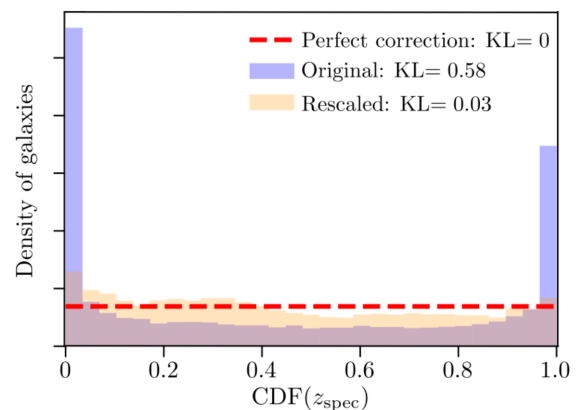
Our COSMOS validation procedure depends on having *griz* photometry and external redshift estimates for objects in the COSMOS field. This field was observed by DES and community programs using DECam. These observations were combined, catalogued, and measured using the same DES pipelines as the survey data; we use the Y1A1 D04 catalogue produced as part of the GOLD catalogues (Drlica-Wagner et al. 2017). MOF magnitudes and Metacal sizes are also measured for all entries in this catalogue. The COSMOS-field observations used herein are  $\approx 1$  mag deeper than the typical Y1 DES data. This mismatch must be kept in mind when using this field for validation (Rau et al. in preparation).

Zero-points for the COSMOS images are determined using the same SLR methods used for the Y1 catalogue. The SLR process is subject to errors that perturb the calibration. We note that the SLR adjustment to the zero-points is below 0.03 mag for most of our data (see fig. A.7 of Drlica-Wagner et al. 2017). The adjustment for Galactic extinction, which is applied as part of the SLR procedure, is of order 0.05 mag in most regions of the survey. In the Y1 data, because it covers a large area with uncorrelated SLR calibrations, there are many independent realizations of these errors and they will average away in the mean  $n^i(z)$ . We must keep in mind, however, that the COSMOS data are based on a single realization of SLR errors, and must therefore allow for the consequent offset of COSMOS photometry from the Y1 mean (Section 4.3).

### 2.2.2 Redshift data and cross-matching

The COSMOS2015 catalogue from Laigle et al. (2016) provides photometry in 30 different ultraviolet/visible/infrared bands, and probability distribution functions (PDFs)  $p^{C30}(z)$  for the redshift of each galaxy based on this photometry using the LEPHARE template-fitting code (Arnouts et al. 1999; Ilbert et al. 2006). Typical,  $p^{C30}(z)$  widths for DES source galaxies are  $\approx 0.01(1+z)$ , far better than the uncertainties in BPZ estimates based on DES *griz* photometry. In Section 6.1, we discuss the influence of errors in  $p^{C30}(z)$ ’s on our  $\Delta z^i$  inferences.

The validation procedure requires assignment of a  $p^{C30}(z)$  to each DES-detectable source in the COSMOS field. After limiting the catalogues to their region of overlap, we associate COSMOS2015 objects with DES GOLD objects with 1.5 arcmin matching radius. Only 0.3 per cent of DES-detected sources fail to match a COSMOS2015 source, and most of these are very near-mask boundaries around bright stars or other peculiar locations. We conclude that ignoring these unmatched sources causes an insignificant bias in the inferred redshift distribution. Of the matched galaxies, 0.4 per cent have no  $p^{C30}(z)$  provided in COSMOS2015, without explanation. For these,



**Figure 1.** The effect of rescaling the COSMOS2015 photometric redshift PDFs using the PIT distribution. The PIT is the redshift CDF values of the full sample of DES-detected sources evaluated at the spectroscopic redshift, for those sources with known  $z_{\text{spec}}$ . The original PDFs (blue) depart significantly from the expected uniform distribution (red dashed line). The  $p^{C30}(z)$  rescaling procedure yields the orange histogram, much improved, as confirmed by the value of the KL divergence between the histogram and a uniform distribution.

we synthesize a  $p^{C30}(z)$  by averaging those of  $\approx 10$  nearest neighbours in the space of COSMOS2015 ZMINCHI2 and *i*-band magnitude, where ZMINCHI2 is the 30-band photometric redshift point prediction corresponding to the minimum  $\chi^2$  fit between fluxes and templates.

We remove from the sample galaxies whose fluxes or pre-seeing sizes could not be measured by the DES pipelines. We note that such objects would be flagged in the lensing source catalogue and removed. A total of 128 563 galaxies with good DES GOLD MOF photometry remain in our final COSMOS sample.

We also use spectroscopic subsamples of this complete sample of galaxies with COSMOS2015 results later to validate our calibration (cf. Section 6.1).

### 2.2.3 PDF rescaling

Following a technique similar to Bordoloi, Lilly & Amara (2010), we rescale the estimated  $p^{C30}(z)$ ’s to make them more accurately represent true distribution functions of redshift.

The method relies on using the subset of COSMOS2015 galaxies with spectroscopic redshifts from the literature (Lilly et al. 2007, 2009a). While this subset is not representative of the full photometric sample (Bonnert et al. 2016; Gruen & Brimiouille 2017), an excess of outliers in true, spectroscopic redshift relative to  $p^{C30}(z)$  is still an indication that the rate of ‘catastrophic failures’ in COSMOS2015 photo- $z$  determinations is higher than that estimated by Laigle et al. (2016). The procedure described here is not a panacea but will lessen such discrepancies.

For each galaxy in COSMOS2015 having a spectroscopic redshift and matching a DES detection,  $p^{C30}(z)$  is integrated to a cumulative distribution function (CDF)  $0 < c(z) < 1$ . The value  $c(z_{\text{spec}})$  for a distribution of objects is the Probability Integral Transform (PIT, Dawid 1984; Angus 1994). If  $p^{C30}(z)$  is a true, statistically rigorous PDF of the spectroscopic redshifts, the PIT values should be uniformly distributed between 0 and 1. In Fig. 1, we show in blue the distribution of PIT values for the original  $p^{C30}(z)$ ’s. The peaks at 0 and at 1 indicate that the widths of the  $p^{C30}(z)$  are underestimated

and need to be broadened, and the asymmetry means that a small global offset should be applied to them.

We recalibrate the  $p^{C30}(z)$ 's by positing that the true PDF can be well approximated by applying the following transformation to the original  $p^{C30}(z)$ :

$$p^{C30}(z) \rightarrow A \cdot p^{C30}(z) \otimes \mathcal{N}(\mu, \sigma) + \frac{1 - A}{\pi\gamma \left[ 1 + \left( \frac{z - (z_0 + \mu)}{\gamma} \right)^2 \right]}. \quad (2)$$

In the first term,  $p^{C30}(z)$  is slightly broadened and shifted by convolution with a Gaussian of width  $\sigma$  and centre  $\mu$ . The second term adds in a Cauchy distribution about the median value  $z_0$  of the original  $p^{C30}(z)$  to allow for long tails. The free parameters  $\{A, \mu, \sigma, \gamma\}$  are found using the Nelder–Mead method of `scipy.stats.minimize` to minimize the Kullback–Leibler (KL) divergence between the histogram of Continuous Rank Probability Score (CRPS) values and the expected uniform distribution. The best-fitting recalibration parameters are derived using a randomly selected 50 per cent of the spectroscopic catalogue and then validated on the remaining 50 per cent. The histogram of CRPS of the validation samples after  $p^{C30}(z)$  recalibration is shown in Fig. 1 by the orange histograms.

Going into further detail, we determine the best-fitting remapping parameters independently for six subsets in bins of  $i$ -band MAG\_AUTO (Bertin & Arnouts 1996) magnitude bounded by [16.1, 20.72, 21.48, 21.98, 22.40, 23.03, 99]. The bins are chosen so that they are each populated by approximately 4000 spectra. Remapping in bins of magnitude is seen to yield lower KL values than remapping in redshift bins, or with no binning. We find that the KL values of the training data and the validation data are very similar, indicating that we are not overfitting. The KL divergences in the first and the last bins decrease from  $0.88 \rightarrow 0.14$  and  $0.52 \rightarrow 0.13$ , respectively, with even greater improvement for the full sample as noted in Fig. 1. The only parameter relevant for the mean redshift calibration performed in Section 4 is the shift in the mean of the  $p(z)$ ,  $\mu$ . The sizes of these in each magnitude bin are all  $|\mu| \leq 0.001$ , much smaller than the uncertainty of our ensemble mean redshifts.

### 2.3 Simulated sky catalogues

We also draw upon simulated data sets generated specifically for the DES collaboration. Specifically, we make use of the BUZZARD-v1.1 simulation, a mock DES Y1 survey created from a set of dark-matter-only simulations. This simulation and the galaxy catalogue construction are described in detail elsewhere (DeRose et al. in preparation; Wechsler et al. in preparation; MacCrann et al. in preparation), so here we provide only a brief overview. BUZZARD-v1.1 is constructed from a set of three  $N$ -body simulations run using L-GADGET2, a version of GADGET2 modified for memory efficiency, with box lengths ranging from 1 to  $4 h^{-1}$  Gpc from which light-cones were constructed on the fly.

Galaxies are added to the simulations using the Adding Density Dependent GALaxies to Light-cone Simulations algorithm (Wechsler et al. in preparation). Spectral energy distributions (SEDs) are assigned to the galaxies from a training set of spectroscopic data from Sloan Digital Sky Survey Data Release 7 (SDSS DR7) (Cooper et al. 2011) based on local environmental density. These SEDs are integrated in the DES pass bands to generate *griz* magnitudes. Galaxy sizes and ellipticities are drawn from distributions fit to SuprimeCam  $i'$ -band data (Miyazaki et al. 2002). The galaxy positions, shapes, and magnitudes are then lensed using the multiple-plane ray-tracing code, Curved-sky gravitational Lensing for Cos-

mological Light cone simulationS (Becker 2013). The simulation is cut to the DES Y1 footprint, and photometric errors are applied to the lensed magnitudes by copying the noise map of the FLUX\_AUTO measurements in the real catalogue. More explicitly, the error on the observed flux is determined only by the limiting magnitude at the position of the galaxy, the exposure time, and the noise-free apparent magnitude of the galaxy itself.

#### 2.3.1 Science sample selection in simulations

The source–galaxy samples in simulations are selected so as to roughly mimic the selections and the redshift distributions of the METACALIBRATION shear catalogue described in Zuntz et al. (2017). This is done by first applying flux and size cuts to the simulated galaxies so as to mimic the thresholds used in the Y1 data by using the Y1 depth and PSF maps. The WL effective number density  $n_{\text{eff}}$  in the simulation is matched to a preliminary version of the shape catalogues, and is about 7 per cent higher than for the final, unblinded METACALIBRATION catalogue. Truth values for redshift, flux, and shear are of course available as well as the simulated measurements.

COSMOS-like catalogues are also generated from the BUZZARD simulated galaxy catalogues by cutting out 367 non-overlapping COSMOS-shaped footprints from the simulation.

## 3 PHOTOMETRIC REDSHIFT ESTIMATION

In this section, we describe the process of obtaining photometric redshifts for DES galaxies. We note that we only use the  $g$ ,  $r$ ,  $i$ , and  $z$  DES bands in this process. We have found that the  $Y$  band adds little to no predictive power.

### 3.1 Bayesian photometric redshifts

Posterior probabilities  $p^{PZ}(z)$  were calculated for each source galaxy using BPZ\*, which is a variant of the Bayesian algorithm described by Benítez (2000), and has been modified to provide the photometric redshift point predictions and PDFs required by the DES collaboration directly from FITS-format input fluxes, without intermediate steps. The BPZ\* code is a distilled version of the distributed BPZ code, and in particular assumes the synthetic template files for each filter have already been generated. Henceforth, we will refer to these simply as ‘BPZ’ results.

#### 3.1.1 Per-galaxy posterior estimation

The redshift posterior is calculated by marginalizing over a set of interpolated model spectral templates, where the likelihood of a galaxy’s photometry belonging to a given template at a given redshift is computed via the  $\chi^2$  between the observed photometry and those of the filter passbands integrated over the model template. The model templates are grouped into three classes, nominally to represent elliptical, spiral, and starburst galaxies. These classes, it is assumed, follow distinct redshift-evolving luminosity functions which can be used to create a magnitude-dependent prior on the redshift posterior of each object, a.k.a. the ‘luminosity prior’. The prior comprises two components, a spectral class prior which is dependent only on observed magnitude, and the redshift prior of each class – which is itself also magnitude dependent (see Benítez 2000 for more detail).

Six base template spectra for BPZ are generated based on original models by Coleman, Wu & Weedman (1980) and Kinney et al.

(1996). The SLR used for the DES Y1 data ensures uniformity of colour across the footprint, but there may be small differences in calibration with respect to the empirical templates we wish to use. Moreover, these original templates are derived from galaxies at redshift zero, while our source galaxies cover a wide range in redshift, with an appreciable tail as high as  $z \sim 1.5$ . The colours of galaxies evolve significantly over this redshift range, even at fixed spectral type. Failure to account for this evolution can easily introduce biases in the redshift posteriors that subsequently require large model bias corrections (see Bonnett et al. 2016, for instance). To address these two issues, we compute evolution/calibration corrections to the template fluxes.

We match low-resolution spectroscopic redshifts from the PRIMUS DR1 data set (Coil et al. 2011; Cool et al. 2013) to high signal-to-noise (S/N) DES photometry and obtain the best fit of the six basic templates to each of the highest quality PRIMUS Multi-Object Survey (PRIMUS) objects (quality = 4) at their spectroscopic redshift. The flux of each template in each filter is then corrected as a function of redshift by the median offset between the DES photometry and the template prediction, in a sliding redshift window of width  $\delta z = 0.06$ . The calibration sample numbers 72 176 galaxies and reaches the full depth of our science sample ( $i_{\text{DES}} < 23.5$ ), while maintaining a low rate of mis-assigned redshifts.<sup>3</sup> Although the incompleteness in PRIMUS is broadly independent of galaxy colour (Cool et al. 2013) and each template is calibrated separately, we nevertheless expect small residual inaccuracies in our calibration to remain. Our COSMOS and WZ validation strategies serve to calibrate such errors in BPZ assignments.

A complete galaxy sample is required for deriving the luminosity prior we use with BPZ. No spectroscopic samples are complete to the limit of our source galaxy sample, and so we turn to the accurate photometric redshift sample in the COSMOS field from Laigle et al. (2016), which is complete to the depth of our main survey area despite being selected in the  $K$  band. The prior takes the form of smooth exponential functions (see Benítez 2000), which we fit to the COSMOS galaxy population by determining galaxy types at their photometric redshift. Because BPZ uses smooth functions rather than the population directly, the luminosity prior used for obtaining posterior redshift probabilities does not replicate the high-frequency line-of-sight structure in the COSMOS field.

BPZ is run on the MOF fluxes (see Section 2) to determine  $p^{\text{PZ}}(z)$  for METACALIBRATION and IM3SHAPE, while for the five METACALIBRATION catalogues – the real one and the four artificially sheared versions – BPZ is run on the METACALIBRATION fluxes to determine bin assignments (cf. Section 3.3 for details). The luminosity prior is constructed from MOF  $i$ -band fluxes for both catalogues. For the BUZZARD simulated galaxy catalogues, BPZ is run on the single mock flux measurement produced in the simulation.

We also explored a further post-processing step as in Section 2.2.3, but applied to the DES BPZ photo- $z$  PDFs. We used the spectroscopic training data, which is not used in BPZ, to recalibrate the PDFs in bins of  $i$ -band magnitude. We find that this rescaling did not noticeably change the mean or widths of the PDFs on average, and that the statistical properties of the redshift distributions in each tomographic bin also remain unchanged.

<sup>3</sup>The outlier fraction of 7.85 per cent quoted in Cool et al. (2013) includes all objects that lie more than  $\delta z > 0.025$  from their true redshift. The difference in template photometry caused by such a small change in redshift is well within the scatter of our computed DES-template offsets. Of greater concern is the fraction of objects with large redshift differences, which is  $< 4$  per cent.

### 3.1.2 Known errors

During BPZ processing of the Y1 data, three configuration and software errors were made.

First, the METACALIBRATION catalogues were processed using MOF  $i$ -band magnitudes for evaluating the BPZ prior rather than Metacal fluxes. This is internally consistent for BPZ, but the use of flux measurements that do not exist for artificially sheared galaxies means that the METACALIBRATION shear estimates are not properly corrected for selection biases resulting from redshift bin assignment. We note that small perturbations to the flux used for assigning the luminosity prior have very little impact on the resulting mean redshift and the colours used by BPZ in this run are correctly measured by METACALIBRATION on unsheared and sheared galaxy images. Rerunning BPZ with the correct, Metacal inputs for  $i$ -band magnitude on a subset of galaxies indicates that the induced multiplicative shear bias is below 0.002 in all redshift bins, well below both the level of statistical errors in DES Y1 and our uncertainty in shear bias calibration. We therefore decide to tolerate the resulting systematic uncertainty.

Second, the SLR adjustments to photometric zero-points were not applied to the observed Metacal fluxes in the Y1 catalogues before input to BPZ. The principal result of this error is that the observed magnitudes are no longer corrected for Galactic extinction. This results in a shift in the average  $n^i(z)$  of the source population of each bin, and a spatially coherent modulation of the bin occupations and redshift distributions across the survey footprint. In Section 4, we describe a process whereby the mean  $n^i(z)$  can be accurately estimated by mimicking the SLR errors on the COSMOS field. In Appendix B, we show that the spurious spatial variation of the redshift distributions causes negligible errors in our estimation of the shear two-point functions used for cosmological inference, and zero error in the galaxy–galaxy lensing estimates.

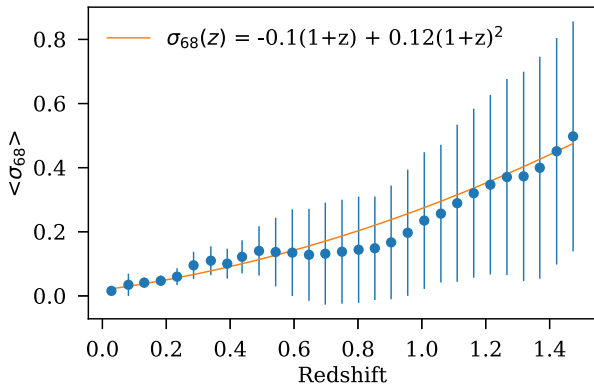
Finally, when rewriting BPZ for a faster version, BPZ\*, two bugs were introduced in the prior implementation, one causing a bias for bright galaxies ( $i$ -band magnitude  $< 18.5$ ) and another which forced uniform prior abundance for the three galaxy templates. These bugs were discovered too late in the DES Y1 analysis to fix. They cause differences in  $\Delta z$  that are subdominant to our calibration uncertainties (below 0.006 among all individual bins). In addition, they are fully calibrated by both COSMOS (which uses the same implementation) and WZ, and hence do not affect our cosmological analysis. We have since implemented all of the above bug fixes, and applied the SLR adjustments correctly, and find negligible changes in the shape and mean of the BPZ PDFs, which are fully within the combined systematic uncertainties.

### 3.1.3 Per-galaxy photo- $z$ precision

While  $n^i(z)$  are the critical inputs to cosmological inference, it is sometimes of use to know the typical size of the redshift uncertainty for individual galaxies. We define  $\sigma_{68}$  for each  $p^{\text{PZ}}(z)$  as the half-width of the 68 percentile region around the median. We select 200 000 galaxies from the METACALIBRATION catalogue at random, and determine the average  $\sigma_{68}$  in bins of redshift according to the median of  $p^{\text{PZ}}(z)$ . We find that this mean  $\sigma_{68}(z)$  is well fit by a quadratic polynomial in mean BPZ redshift and present the best-fitting parameters in Fig. 2.

Further metrics of the performance of individual galaxies' photo- $z$ 's but with respect to truth redshifts are provided in Section 4.7.





**Figure 2.** The average width of the posterior distributions of BPZ photometric redshifts for data selected in bins of mean BPZ redshift. The posterior width is defined as the 68 percent spread of the PDF  $p^{PZ}(z)$  about its median. The error bars correspond to the standard deviation of the individual source's  $\sigma_{68}$  around the average.

### 3.2 Directional Neighbourhood Fitting

Directional Neighbourhood Fitting (DNF, De Vicente et al. 2016) is a machine-learning algorithm for galaxy photometric redshift estimation. We have applied it to reconstruct the redshift distributions for the METACALIBRATION catalogues. DNF takes as reference a training sample whose spectroscopic redshifts are known. Based on the training sample, DNF constructs the prediction hyperplane that best fits the neighbourhood of each target galaxy in multiband flux space. It then uses this hyperplane to predict the redshift of the target galaxy. The key feature of DNF is the definition of a new neighbourhood, the Directional Neighbourhood. Under this definition – and leaving apart degeneracies corresponding to different galaxy types – two galaxies are neighbours not only when they are close in the Euclidean multiband flux space, but also when they have similar relative flux in different bands, i.e. colours. In this way, the neighbourhood does not extend in multiband flux hyperspheres but in elongated hypervolumes that better represent similar colour, and presumably similar redshift. As described in Section 3.3, these DNF photo- $z$  predictions are used to classify the galaxies in tomographic redshift bins.

A random sample from the  $p^{PZ}(z)$  of an object is approximated in the DNF method by the redshift of the nearest neighbour within the training sample. It is used as the sample for  $n^i(z)$  reconstruction and interpreted in Section 3.3 as a random draw from the underlying per-galaxy posterior.

The training sample used for Y1 DNF prediction was collected by the DES Science Portal team (Gschwend et al. 2017) from different spectroscopic surveys and includes the VIMOS Public Extragalactic Redshift Survey (VIPERS) second data release (Scodreggio et al. 2016). The validation of the predictions was based on COSMOS2015 photo- $z$ 's. Objects near the COSMOS data were removed from the training sample. Since the machine learning algorithm can correct for imperfections in the input photometry giving a representative training set, both training and photo- $z$  predictions are based on Metacal photometry without SLR adjustments, for all runs on DNF.

The fiducial DES Y1 cosmological parameter estimation uses the BPZ photo- $z$ 's, and DES Collaboration et al. (2017) demonstrate that these estimates are robust to substitution of DNF for BPZ.

The  $n^i(z)$  distributions of BPZ and DNF are not expected to be identical, because the algorithms may make different bin assignments

for the same source. We therefore do not offer a direct comparison. We do, however, repeat for DNF all of the validation processes described herein for the BPZ  $n^i(z)$  estimates. The results for DNF are given in Appendix C.

### 3.3 Binning and initial $n^i(z)$ estimation

Both photo- $z$  codes yield six different posterior distributions  $p^{PZ}(z_j)$  for each galaxy  $j$  in the Y1 shape catalogues, conditional on either the MOF, the unsheared Metacal, or the four sheared Metacal flux measurements. In this section, we describe how these are used to define source redshift bins  $i$  and provide an initial estimate of the lensing-weighted  $n^i(z)$  of each of these bins. Table 1 gives an overview of these steps.

Galaxies are assigned to bins based on the expectation value of their posterior,  $\langle z_j \rangle = \int z_j p^{PZ}(z_j) dz_j$ . We use four bins between the limits  $[0.20, 0.43, 0.63, 0.90, 1.30]$ . These tomographic boundaries exclude  $\langle z_j \rangle < 0.2$  and  $\langle z_j \rangle > 1.3$  that have large photo- $z$  biases. We place three tomographic bins at  $\langle z_j \rangle < 0.9$  with approximately equal effective source density  $n_{\text{eff}}$ , a proxy for the statistical uncertainty of shear signals in the METACALIBRATION catalogue, since  $z = 0.9$  is the upper limit of the WZ constraints. The fourth bin,  $0.9 < \langle z_j \rangle < 1.3$ , is thus validated only by the COSMOS method.

For METACALIBRATION sources, this bin assignment is made based on the  $\langle z_j \rangle$  of the photo- $z$  run on Metacal photometry, instead of MOF photometry. The reason for this is that flux measurements, and therefore photo- $z$  bin assignments, can depend on the shear a galaxy is subject to. This can cause selection biases in shear due to photo- $z$  binning, which can be corrected in METACALIBRATION. The latter requires that the bin assignment can be repeated using a photo- $z$  estimate made from measurements made on artificially sheared images of the respective galaxy (cf. Huff & Mandelbaum 2017; Sheldon & Huff 2017; Zuntz et al. 2017), and only the Metacal measurement provides that.

For IM3SHAPE sources, the bin assignment is made based on the  $\langle z_j \rangle$  of the photo- $z$  run on MOF photometry, which has higher S/N and lower susceptibility to blending effects than Metacal photometry. This provides more precise (and possibly more accurate) photo- $z$  estimates.

We note that this means that for each combination of shear and photo- $z$  pipeline, bin assignments and effective weights of galaxies are different. The redshift distributions and calibrations derived below can therefore not be directly compared between the different variants.

The stacked redshift distribution  $n^i(z)$  of each of the tomographic bins is estimated by the lensing-weighted stack of random samples  $z_j^{PZ}$  from the  $p^{PZ}(z_j)$  of each of all galaxies  $j$  in bin  $i$ . Given the millions of galaxies in each bin, the noise due to using only one random sample from each galaxy is negligible. For both the METACALIBRATION and IM3SHAPE catalogues, we use random samples from the  $p^{PZ}(z)$  estimated by BPZ run on MOF photometry to construct the  $n^i(z)$ , this being the lower noise and more reliable flux estimate. In the case of DNF, we use the Metacal photometry run for both the binning and initial  $n^i(z)$  estimation.

By the term *lensing weighted* above, we mean the effective weight  $w_j^{\text{eff}}$  a source  $j$  has in the lensing signals we measure in Troxel et al. (2017) and Prat et al. (2017). In the case of METACALIBRATION, sources are not explicitly weighted in these papers. Since the ellipticities of galaxies in METACALIBRATION have different responses to shear (Huff & Mandelbaum 2017; Sheldon & Huff 2017), and since we measure correlation functions of METACALIBRATION ellipticities that we then correct for the mean response of the ensemble, however,



**Table 1.** Binning,  $n^i(z)$  estimation, and mean  $z$  calibration for the variants of the shear and photo- $z$  catalogues.

| Shear catalogue | Step                  | BPZ                                | DNF                                |
|-----------------|-----------------------|------------------------------------|------------------------------------|
| METACALIBRATION | Binned by:            | Metacal $griz \langle z_j \rangle$ | Metacal $griz \langle z_j \rangle$ |
|                 | $n^i(z)$ by stacking: | MOF $griz z_j^{PZ}$                | Metacal $griz z_j^{PZ}$            |
|                 | Calibration by:       | COSMOS + WZ                        | COSMOS + WZ                        |
| IM3SHAPE        | Binned by:            | MOF $griz \langle z_j \rangle$     | –                                  |
|                 | $n^i(z)$ by stacking: | MOF $griz z_j^{PZ}$                | –                                  |
|                 | Calibration by:       | COSMOS + WZ                        | –                                  |

sources do have an effective weight that is proportional to their response. As can be derived by considering a mixture of subsamples at different redshifts and with different mean response, the correct redshift distribution to use is therefore one weighted by  $w_j^{\text{eff}} \propto (R_{y1,j} + R_{y2,j})$ , where the  $R$ 's are shear responses defined in Zuntz et al. (2017). In the case of IM3SHAPE, explicit weights  $w_j$  are used in the measurements, and sources have a response to shear  $(1 + m_j)$  with the calibrated multiplicative shear bias  $m_j$  (Zuntz et al. 2017). The correct effective weights for IM3SHAPE are therefore  $w_j^{\text{eff}} \propto (1 + m_j) \times w_j$ .

We note that for other uses of the shape catalogues, such as with the optimal  $\Delta\Sigma$  estimator (Sheldon et al. 2004), the effective weights of sources could be different, which has to be accounted for in the photo- $z$  calibration.

#### 4 VALIDATING THE REDSHIFT DISTRIBUTION USING COSMOS MULTIBAND PHOTOMETRY

In Bonnett et al. (2016), we made use of COSMOS photometric redshifts as an independent estimate and validation of the redshift distribution of the WL source galaxies. We made cuts in magnitude, full width at half-maximum, and surface brightness to the source catalogue from DECam images in the COSMOS field that were depth-matched to the main survey area. These cuts approximated the selection function of the shape catalogues used for the cosmic shear analysis. Similar techniques that find COSMOS samples of galaxies matched to a lensing source catalogue by a combination of magnitude, colour, and morphological properties have been applied by numerous studies (Applegate et al. 2014; Hoekstra et al. 2015; Okabe & Smith 2016; Cibirka et al. 2017; Amon et al. 2018). In this work, we modify the approach to reduce statistical and systematic uncertainty on its estimate of mean redshift and carefully estimate the most significant sources of systematic error.

We wish to validate the  $n^i(z)$  derived for a target sample A of galaxies using a sample B with known redshifts. Ideally, for every galaxy in A, we would find a galaxy in B that looks exactly like it when observed in the same conditions. The match would need to be made in all properties we use to select and weight the galaxy in the WL sample that also correlate with redshift.

Then, the mean redshift distribution of the matched B galaxies, weighted the same way as the A galaxies are for WL measures, will yield the desired  $n^i(z)$ . This goal is unattainable without major observational, image processing, and simulation efforts, but we can approximate it with a method related to the one of Lima et al. (2008) and estimate the remaining uncertainties. We also need to quantify uncertainties resulting from the finite size of sample B, and from possible errors in the ‘known’ redshifts of B. Here, our sample A are the galaxies in either the IM3SHAPE or METACALIBRATION Y1 WL

catalogues, spread over the footprint of DES Y1, and sample B is the COSMOS2015 catalogue of Laigle et al. (2016).

#### 4.1 Methodology

We begin by selecting a random subsample of 200 000 galaxies from each WL source catalogue, spread over the whole Y1 footprint, and assigning to each a match in the COSMOS2015 catalogue. The match is made by  $griz$  MOF flux and pre-seeing size (not by position), and the matching algorithm proceeds as follows, for each galaxy in the WL source sample:

(i) Gaussian noise is added to the DES  $griz$  MOF fluxes and sizes of the COSMOS galaxies until their noise level is equal to that of the target galaxy. COSMOS galaxies whose flux noise is above that of the target galaxy are considered ineligible for matching. While this removes 13 per cent of potential DES–COSMOS pairs, this is unlikely to induce redshift biases, because the noise level of the COSMOS  $griz$  catalogue is well below that of the Y1 survey in most regions of either, so it should be rare for the true COSMOS ‘twin’ of a Y1 source to have higher errors. The discarded pairs predominantly are cases of large COSMOS and small Y1 galaxies (since large size raises flux errors), and the size mismatch means these galaxies would never be good matches. Other discarded pairs come from COSMOS galaxies lying in a shallow region of the DECam COSMOS footprint, such as near a mask or a shallow part of the dither pattern, and this geometric effect will not induce a redshift bias. Note that the MOF fluxes used here make use of the SLR zero-points, for both COSMOS and Y1 catalogues. The size metric is the one produced by METACALIBRATION.

(ii) The matched COSMOS2015 galaxy is selected as the one that minimizes the flux-and-size  $\chi^2$ ,

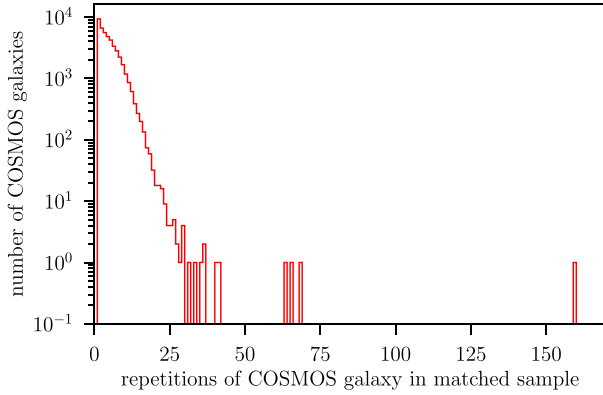
$$\chi^2 \equiv \sum_{b \in \text{griz}} \left( \frac{f_b^{Y1} - f_b^{\text{COSMOS}}}{\sigma_b} \right)^2 + \left( \frac{s^{Y1} - s^{\text{COSMOS}}}{\sigma_s} \right)^2, \quad (3)$$

where  $f_b$  and  $s$  are the fluxes in band  $b$  and the size, respectively, and  $\sigma_b$  and  $\sigma_s$  are the measurement errors in these for the chosen source. We also find the galaxy that minimizes the  $\chi_{\text{flux}}^2$  from flux differences only:

$$\chi_{\text{flux}}^2 \equiv \sum_{b \in \text{griz}} \left( \frac{f_b^{Y1} - f_b^{\text{COSMOS}}}{\sigma_b} \right)^2. \quad (4)$$

If the least  $\chi_{\text{flux}}^2$  is smaller than  $(\chi^2 - 4)$  of the galaxy with the least flux-and-size  $\chi^2$ , we use this former galaxy instead. Without this criterion, we could be using poor matches in flux (which is more predictive of redshift than size) by requiring a good size match (that does not affect redshift distributions much). It applies to about 15 per cent of cases.

(iii) A redshift  $z^{\text{true}}$  is assigned by drawing from the  $p^{C30}(z)$  of the matched COSMOS2015 galaxy, using the rescaling of Section 2.2.3.



**Figure 3.** Repetitions of COSMOS galaxies in the fiducial matched METACALIBRATION sample of 200 000 objects. The overall weight of galaxies with more than 20 matches, which are typically bright, is below one per cent of the total weight. The high-usage outliers are a few of the very bright COSMOS galaxies.

(iv) A bin assignment is made by running the BPZ procedures of Section 3.1 on the noise-matched *griz* fluxes of the COSMOS match, using the mean value of each galaxy’s posterior  $p^{\text{PZ}}(z)$ , as before. For the IM3SHAPE catalogue, the MOF photometry of the COSMOS galaxy is used, just as is done for the Y1 main survey galaxies. The METACALIBRATION treatment is more complex: we generate simulated Metacal fluxes  $f_b^{\text{meta,COSMOS}}$  for the COSMOS galaxy via

$$f_b^{\text{meta,COSMOS}} = f_b^{\text{MOF,COSMOS}} \frac{f_b^{\text{meta,Y1}}}{f_b^{\text{MOF,Y1}}} \quad (5)$$

This has the effect of imposing on COSMOS magnitudes the same difference between Metacal and MOF as is present in Y1, thus imprinting on to COSMOS simulations any errors in the Y1 catalogue METACALIBRATION magnitudes due to neglect of the SLR or other photometric errors. For the flux uncertainty of these matched fluxes, for both MOF and Metacal, we assign the flux errors of the respective Y1 galaxy.

(v) The effective WL weight  $w$  of the original source galaxy is assigned to its COSMOS match (cf. Section 3.3).

As a check on the matching process, we examined the distribution of the  $\chi^2_{\text{flux}}$  between matched galaxies. The distribution is skewed towards significantly lower  $\chi^2$  values than expected from a true  $\chi^2$  distribution with 4 degrees of freedom. This indicates that the COSMOS-Y1 matches are good: COSMOS galaxies are photometrically even more similar to the Y1 target galaxies than they would be to re-observed versions of themselves.

A second check on the matching algorithm is to ask whether the individual COSMOS galaxies are being resampled at the expected rates. As expected, most sufficiently bright galaxies in COSMOS are used more than once, while the faintest galaxies are used more rarely or never. Fig. 3 shows the number of times each of the COSMOS galaxies is matched to METACALIBRATION (if it is bright enough to be matched at all) in our fiducial matched catalogue. We see that there is no unwanted tendency for a small fraction of the COSMOS galaxies to bear most of the resampling weight. All COSMOS galaxies with more than 50 repetitions are brighter than  $i = 18.5$  and have a typical redshift of  $z \approx 0.15$ .

We now use the matched COSMOS galaxy set to produce an estimate of the difference in mean redshift between the *griz*-predicted distribution and the ‘truth’ provided by COSMOS2015 for all galax-

ies assigned to a given source bin:

$$\Delta z = \frac{\sum_i w_i z_i^{\text{true}}}{\sum_i w_i} - \frac{\sum_j w_j z_j^{\text{PZ}}}{\sum_j w_j}, \quad (6)$$

where the sums run over all matched COSMOS2015 galaxies  $i$  and all galaxies in the original source sample  $j$ .

This construction properly averages  $\Delta z$  over the observing conditions (including photometric zero-point errors) and weights of the Y1 WL sources. These estimated  $\Delta z$  values using BPZ are tabulated in Table 2 for both WL source catalogues.

The COSMOS validation also yields an estimate of  $n^i(z)$  by a weighted average of the rescaled  $p^{\text{C30}}(z)$ ’s of the matches (or, equivalently, of samples drawn from them). Fig. 4 plots these resampled-COSMOS estimates along with the original  $n_{\text{PZ}}^i(z)$  from BPZ. Here, it is apparent that in some bins, these two estimates differ by more than just a simple shift in redshift – the shapes of the  $n^i(z)$  distributions differ significantly. In Section 6.2, we demonstrate that these differences do not bias our cosmological inferences.

In the following subsections, we determine several contributions to the uncertainty of these  $\Delta z^i$ . All of these are presented for the METACALIBRATION sample binned by BPZ redshift estimates. For IM3SHAPE galaxies with BPZ, we use the same uncertainties. Results for DNF are in Appendix C.

From the resampling procedure, we also determine common metrics on the photo- $z$  performance in Section 4.7.

## 4.2 Sample variance contribution

The first contribution to the uncertainty in the COSMOS  $\Delta z^i$ ’s is from sample variance from the small angular size of the COSMOS2015 catalogue. Any attempt at analytic estimation of this uncertainty would be complicated by the reweighting/sampling procedure that alters the native  $n(z)$  of the COSMOS line of sight, so we instead estimate the covariance matrix of the  $\Delta z^i$  by repeating our procedures on different realizations of the COSMOS field in the BUZZARD simulated galaxy catalogues.

The resampling procedure of Section 4.1 is repeated using a fixed single draw of 200 000 galaxies from a BUZZARD simulated Y1 WL sample (Section 2.3) as catalogue A, and 367 randomly placed COSMOS-shaped cutouts from the BUZZARD truth catalogue, i.e. a catalogue with noiseless flux information, as catalogue B. Each of these yields an independent  $n(z)$  of the matched COSMOS catalogues (cf. Fig. 5), and consequently an independent sample variance realization of the  $\Delta z^i$ . There are significant correlations between the  $\Delta z^i$  bins, especially bins 1 and 2, as shown in Section 6. The diagonal elements are listed as ‘COSMOS footprint sampling’ in Table 2.

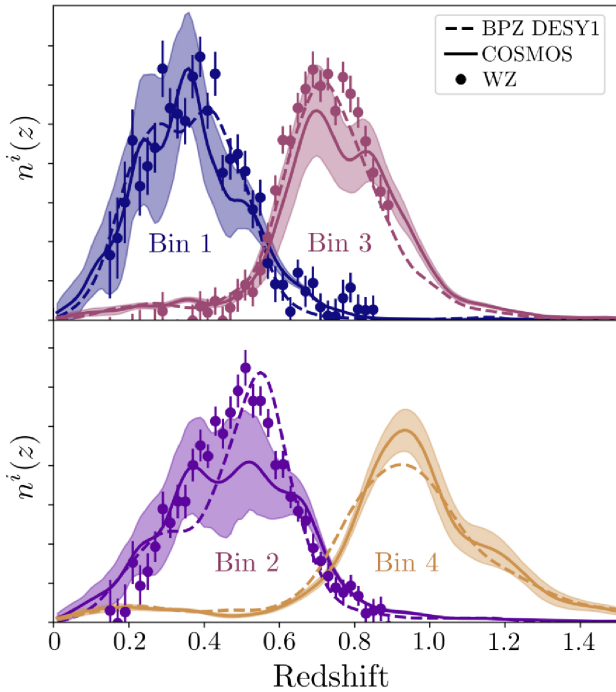
Since we use the same subset of the BUZZARD lensing sample for each of the COSMOS-like resamplings, this variance estimate does not include the uncertainty due to the limited subsample size of 200 000 galaxies. We estimate the latter effect by resampling of the  $\Delta z^i$  in this sample, and find it to be subdominant ( $\sigma_{\Delta z}^i < 0.003$  in all redshift bins, ‘limited sample size’ in Table 2).

## 4.3 Photometric calibration uncertainty

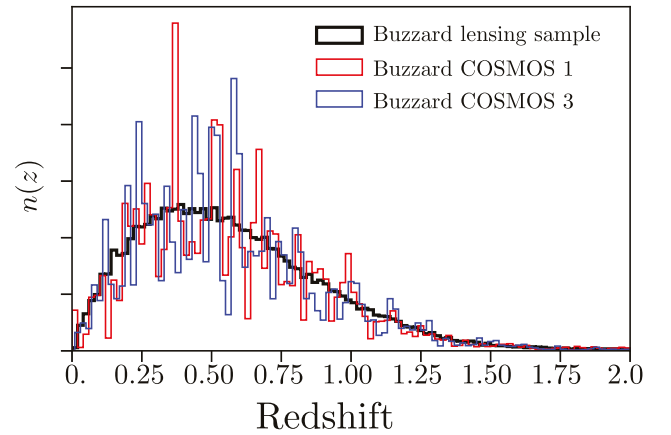
The *griz* DECam photometry of the COSMOS field has uncertainties in its zero-point due to errors in the SLR-based calibration. While the Y1 catalogue averages over the SLR errors of many fields, the validation is sensitive to the single realization of SLR errors in the COSMOS field. We estimate the distribution of zero-point errors by comparing the SLR zero-points in the Y1 catalogue

**Table 2.** Values of and error contributions to photo- $z$  shift parameters of BPZ  $n^i(z)$ .

| Value   | Bin 1              | Bin 2              | Bin 3              | Bin 4              |
|---|--------------------|--------------------|--------------------|--------------------|
| $z^{\text{PZ}}$ range                               | 0.20–0.43          | 0.43–0.63          | 0.63–0.90          | 0.90–1.30          |
| COSMOS footprint sampling                           | $\pm 0.0073$       | $\pm 0.0077$       | $\pm 0.0039$       | $\pm 0.0070$       |
| COSMOS limited sample size                          | $\pm 0.0009$       | $\pm 0.0017$       | $\pm 0.0018$       | $\pm 0.0030$       |
| COSMOS photometric calibration errors               | $\pm 0.0030$       | $\pm 0.0040$       | $\pm 0.0039$       | $\pm 0.0059$       |
| COSMOS hidden variables                             | $\pm 0.0066$       | $\pm 0.0066$       | $\pm 0.0066$       | $\pm 0.0066$       |
| COSMOS errors in matching                           | $\pm 0.0073$       | $\pm 0.0073$       | $\pm 0.0073$       | $\pm 0.0073$       |
| COSMOS single-bin $\Delta z^i$ uncertainty          | $\pm 0.013$        | $\pm 0.013$        | $\pm 0.011$        | $\pm 0.014$        |
| METACALIBRATION                                     |                    |                    |                    |                    |
| COSMOS final $\Delta z^i$ , tomographic uncertainty | $-0.006 \pm 0.020$ | $-0.014 \pm 0.021$ | $+0.018 \pm 0.018$ | $-0.018 \pm 0.022$ |
| WZ final $\Delta z^i$                               | $+0.007 \pm 0.026$ | $-0.023 \pm 0.017$ | $+0.003 \pm 0.014$ | –                  |
| Combined final $\Delta z^i$                         | $-0.001 \pm 0.016$ | $-0.019 \pm 0.013$ | $+0.009 \pm 0.011$ | $-0.018 \pm 0.022$ |
| IM3SHAPE  |                    |                    |                    |                    |
| COSMOS final $\Delta z^i$ , tomographic uncertainty | $+0.001 \pm 0.020$ | $-0.014 \pm 0.021$ | $+0.008 \pm 0.018$ | $-0.057 \pm 0.022$ |
| WZ final $\Delta z^i$                               | $+0.008 \pm 0.026$ | $-0.031 \pm 0.017$ | $-0.010 \pm 0.014$ | –                  |
| Combined final $\Delta z^i$                         | $+0.004 \pm 0.016$ | $-0.024 \pm 0.013$ | $-0.003 \pm 0.011$ | $-0.057 \pm 0.022$ |

**Figure 4.** The redshift distributions  $n^i(z)$  derived from three different methods are plotted for each of the four WL METACALIBRATION source bin populations  $i = 1, \dots, 4$ . The top (bottom) figure shows the first and third (second and fourth) tomographic redshift bins. The clustering methodology (WZ) can only constrain  $n^i(z)$  for  $0.15 < z < 0.9$ , and the normalization of the distribution is arbitrary for the bins extending beyond this range. The band around the COSMOS  $n^i(z)$  depicts the uncertainties as described in Section 4 and Table 2, and the error bars on WZ are statistical noise. There is some significant disagreement in the shapes of the distributions, particularly in  $n^2(z)$ . We demonstrate in Section 6.2 that this does not bias the DES Y1 cosmological inferences.

to those derived from the superior ‘forward global calibration module’ (FGCM) and reddening correction applied to three years’ worth of DES exposures by Burke et al. (2017). In this, we only use regions with Galactic extinction  $E(B - V) < 0.1$ , since the COSMOS field has relatively low extinction and strong reddening might cause larger differences between the FGCM and SLR calibration. The

**Figure 5.** Redshift distributions of the full simulated lensing sample from the BUZZARD catalogue (grey) and two examples of samples from COSMOS-sized footprints in the BUZZARD catalogues that have been resampled and weighted to match the full distribution (blue and orange).

root-mean-square zero-point offsets between SLR and FGCM calibration are between 0.007 ( $z$ ) and 0.017 ( $g$ ).

We estimate the impact on  $\Delta z^i$  by drawing 200 mean-subtracted samples of photometric offsets from the observed (FGCM-SLR) distribution, applying each to the COSMOS fluxes, and repeating the derivation of  $\Delta z^i$  as per Section 4.1. Table 2 lists the uncertainty of the  $\Delta z^i$  of each of the four tomographic bins due to those, which are 0.003–0.006.

#### 4.4 Hidden-variable uncertainty

We have matched COSMOS galaxies to the shear catalogue galaxies by their  $griz$  fluxes and by their estimated pre-seeing size. This set of parameters is likely not completely predictive of a galaxy’s selection and weight in our shear catalogue. Other morphological properties (such as the steepness of its profile) probably matter and do correlate with redshift (e.g. Soo et al. 2017). In addition, the matching in size is only done in 85 per cent of cases to begin with Section 4.1.

To estimate the effect of any variables hidden to our matching algorithm, we repeat the process while ignoring the size variable. We find changes in  $\Delta z^i$  for METACALIBRATION to be (+0.010, +0.015, +0.009, +0.014) in the four bins. Soo et al. (2017) found that the

single morphological parameter that provides the greatest improvement in  $\sigma_{68}$  and outlier fraction is galaxy size. Since we therefore expect the size to have the strongest influence on both lensing and redshift, and we are correcting for size, we estimate the potential influence of any further variables as no more than half of the size effect. We do not assume that these systematic errors found in simulations are exactly equal in the data – rather, we only assume that the two are of similar size, and thus use the rms of offsets found in the simulation as the width of a Gaussian systematic uncertainty on the data. We take half of the quadratic mean of the shifts in the four redshift bins,  $\pm 0.0066$ , as our estimate of the hidden-variable uncertainty in each bin. These biases are likely to be correlated between bins. In Section 4.6, we describe a modification to our single-bin uncertainties that accounts for potential correlations.

#### 4.5 Systematic errors in matching

Even in the absence of the above uncertainties, the resampling algorithm described above might not quite reproduce the true redshift distribution of the input sample. The matching algorithm may not, for example, pick a COSMOS galaxy which is an unbiased estimator of the target galaxy’s redshift, especially given the sparsity and inhomogeneous distribution of the COSMOS sample in the four- to five-dimensional space of *griz* fluxes and size.

We estimate the size of this effect on  $\Delta z^i$  using the *mean* offset in binned mean true redshift of the 367 realizations of resampled COSMOS-like catalogues in the BUZZARD simulations (see Section 4.2) from the binned mean true redshift of the underlying BUZZARD shape sample.

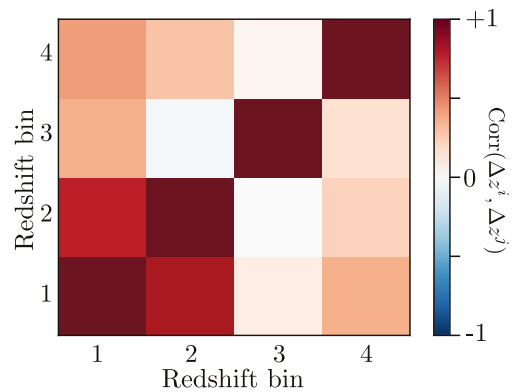
We find differences in mean true redshift of sample A matched B of (0.0027, 0.0101, 0.0094, 0.004) for the four redshift bins. Since the simulation is not fully realistic, we do not attempt to correct the result of our resampling with these values. Rather, we take them as indicators of possible systematic uncertainties of the resampling algorithm. Following the argument in Section 4.4, we thus use the quadratic mean of these values (0.0073) as a systematic uncertainty in each bin.

#### 4.6 Combined uncertainties and correlation between redshift bins

The final uncertainties on the  $\Delta z^i$  are estimated by adding in quadrature the contributions listed above, yielding the ‘COSMOS total  $\Delta z^i$  uncertainty’ in Table 2. These values are derived independently for each redshift bin, but it is certain that the  $\Delta z^i$  have correlated errors, e.g. from sample variance as shown in Fig. 6, and such correlations should certainly be included in the inference of cosmological parameters. The values of the off-diagonal elements of the combined COSMOS  $\Delta z$  covariance matrix, are, however, difficult to estimate with any precision. In Appendix A, we demonstrate that by increasing the diagonal elements of the covariance matrix by a factor  $(1.6)^2$  and nulling the off-diagonal elements, we can ensure that any inferences based on the  $\Delta z^i$  are conservatively estimated for any reasonable values of the off-diagonal elements. We therefore apply a factor of 1.6 to all of the single-bin uncertainties in deriving the ‘COSMOS final  $\Delta z^i$ ’ constraints for METACALIBRATION and IM3SHAPE given in Table 2.

#### 4.7 Standard photo-z performance metrics

Although not a critical input to the cosmological tests of DES Collaboration et al. (2017), we determine here some standard metrics



**Figure 6.** Correlation coefficients of error on  $\Delta z^i$  due to sample variance in COSMOS-resamplings between our four source redshift bins. Shown is the correlation matrix for the METACALIBRATION sample binned by BPZ.

of photo- $z$  performance. We define the residual  $R$  as the difference between the mean of the  $p^{\text{PZ}}(z)$  using the MOF photometry and a random draw from the COSMOS  $p^{\text{C30}}(z)$  matched during resampling. We use a random draw from  $p^{\text{C30}}(z)$  rather than the peak, so that uncertainty in these ‘truth’  $z$ ’s is included in the metrics. Because the width of  $p^{\text{C30}}(z)$  is much smaller than that of  $p^{\text{PZ}}(z)$ , this does not affect the results significantly.

We define  $\sigma_{68}(R)$  as the 68 per cent spread of  $R$  around its median. In this section,  $\sigma_{68}(R)$  measures the departure of the mean of  $p^{\text{PZ}}(z)$  from the true  $z$ , whereas the  $\sigma_{68}$  in Fig. 2 is a measure of width of  $p^{\text{PZ}}(z)$  independent of any truth redshifts. We also measure the outlier fraction, defined as the fraction of data for which  $|R| > 2 \times \sigma_{68}$ . If the redshift distribution were Gaussian, the outlier fraction would be 5 per cent, and this metric is a measure of the tails of the  $R$  distribution.

We calculate the uncertainties on these metrics from sample variance, COSMOS photometric calibration uncertainty, and selection of the lensing sample by hidden variables (cf. Sections 4.2–4.4). We add each of these uncertainties in quadrature in each tomographic bin, and highlight that the largest source of uncertainty is due to sample variance.

Table 3 presents the metric values and uncertainties of the galaxies in each redshift bin, using the METACALIBRATION sample and binning.

### 5 COMBINED CONSTRAINTS

To supplement the constraints on  $\Delta z^i$  derived above using the COSMOS2015 photo- $z$ ’s, we turn to the ‘correlation redshift’ methodology (Newman 2008; Ménard et al. 2013; Schmidt et al. 2013), whereby one measures the angular correlations between the unknown sample (the WL sources) and a population of objects with relatively well-determined redshifts. In our case, the known population are the REDMAGIC galaxies, selected precisely so that their *griz* colours yield high-accuracy photometric redshift estimates.

An important complication of applying WZ to DES Y1 is that we do not have a sufficient sample of galaxies with known redshift available that spans the redshift range of the DES Y1 lensing source galaxies – the REDMAGIC galaxies do not extend beyond  $0.2 < z < 0.9$ . Constraints on the mean redshift of a source population can still be derived in this case, but only by *assuming* a shape for the  $n(z)$  distribution, whose mean is then determined by the clustering signal in a limited redshift interval. A mismatch in shape between the assumed and true  $n(z)$  is a source of systematic uncertainty in such a WZ analysis. One of the main results of Gatti et al. (2017), which



**Table 3.** Common performance metrics and uncertainties measured using BPZ point predictions and draws from the rescaled COSMOS2015 PDFs. The quantity  $\sigma_{68}(R)$  is the 68 per cent spread of the residual distribution  $R$ , about the median. The outlier fraction is defined as the fraction of galaxies with  $griz$  redshift estimates than  $2 \times \sigma_{68}(R)$  from the COSMOS2015 value.

| Metric                                       | $0.20 < z < 0.43$ | $0.43 < z < 0.63$ | $0.63 < z < 0.90$ | $0.90 < z < 1.30$ |
|--|-------------------|-------------------|-------------------|-------------------|
| BPZ METACALIBRATION binning, MOF $p^{PZ}(z)$ |                   |                   |                   |                   |
| $\sigma_{68}(R)$                             | $0.12 \pm 0.01$   | $0.16 \pm 0.01$   | $0.12 \pm 0.01$   | $0.17 \pm 0.01$   |
| Outlier fraction per cent                    | $3.3 \pm 0.5$     | $3.6 \pm 0.8$     | $6.1 \pm 0.4$     | $6.6 \pm 0.5$     |
| DNF METACALIBRATION                          |                   |                   |                   |                   |
| $\sigma_{68}(R)$                             | $0.10 \pm 0.01$   | $0.16 \pm 0.01$   | $0.16 \pm 0.01$   | $0.21 \pm 0.01$   |
| Outlier fraction per cent                    | $5.0 \pm 0.4$     | $3.8 \pm 0.8$     | $8.6 \pm 0.6$     | $7.5 \pm 0.5$     |

describes the implementation and full estimation of uncertainties of the WZ method for DES Y1 source galaxies, is that while this systematic uncertainty needs to be accounted for, it is not prohibitively large. This statement is validated in Gatti et al. (2017) for the degree of mismatch between the true  $n(z)$  and the  $n(z)$  found in a number of photometric redshift methods applied to simulated galaxy catalogues. The redshift distributions of the DES weak lensing sources as estimated by BPZ, as far as we can judge this from the comparison with the COSMOS estimates of their true  $n(z)$ , show a similar level of mismatch to the truth. The systematic uncertainty budget derived in Gatti et al. (2017) is therefore applicable to the data. We do not, however, attempt to correct the systematic offsets in WZ estimates of  $\Delta z^i$  introduced due to this effect – for this, we would require the galaxy populations and photometric measurements in the simulations to be perfectly realistic.

The method is applied to DES Y1 data in Davis et al. (2017). A similar analysis was performed on the DES SV data set in Davis et al. (2018). The resultant estimates of  $\Delta z^i$  are listed in Table 2 and plotted in Fig. 7. The full  $n^i(z)$ 's estimated from the WZ method are plotted in Fig. 4. Note that the WZ method obtains no useful constraint for bin 4 because the REDMAGIC sample is confined to  $z < 0.9$  and thus has little overlap with bin 4. Due to the lack of independent confirmation, the redshift calibration of this bin should be used with greater caution – in DES Collaboration et al. (2017) and Gruen et al. (2017), we indeed show that constraints do not significantly shift when the bin is removed from the analysis.

In the three lower redshift bins, the COSMOS and WZ validation methods generate estimates of  $\Delta z^i$  that are fully consistent. Indeed even their  $n^i(z)$  curves show qualitative agreement. We therefore proceed to combine their constraints on  $\Delta z^i$  to yield our most accurate and reliable estimates. The statistical errors of the COSMOS and WZ methods are uncorrelated (sample variance in the COSMOS field versus shot noise in the measurements of angular correlations in the wide field). The dominant systematic errors of the two methods should also be uncorrelated, e.g. shortcomings in our re-sampling for COSMOS versus uncertainties in the bias evolution of source galaxies for WZ. We are therefore confident that we can treat the COSMOS and WZ constraints as independent, and we proceed to combine them by multiplying their respective one-dimensional Gaussian distributions for each  $\Delta z^i$ , i.e. inverse-variance weighting. In bin 4, the final constraints are simply the COSMOS constraints since WZ offers no information.

The resultant constraints, listed for both METACALIBRATION and IM3SHAPE catalogues in Table 2, are the principal result of this work, and are adopted as input to the cosmological inferences of Troxel et al. (2017) and DES Collaboration et al. (2017). The adopted 68 per cent-confidence ranges for each  $\Delta z^i$  are denoted by the grey bands in the one-dimensional marginal plots of Fig. 7.

One relevant question is whether our calibration finds that significant non-zero shifts are required to correct the photo- $z$  estimates of the mean redshift. For the fiducial METACALIBRATION BPZ, this is not the case: the  $\chi^2 = \sum_i (\Delta z^i / \sigma_{\Delta z^i})^2$  is 3.5 with 4 bins. However, the combined  $\Delta z^4$  is non-zero at  $2.6\sigma$  for IM3SHAPE BPZ and the  $\Delta z^2$  is non-zero at  $3.3\sigma$  for METACALIBRATION DNF, indicating that there are significant alterations being made to some of the  $n_{PZ}^i(z)$  estimates.

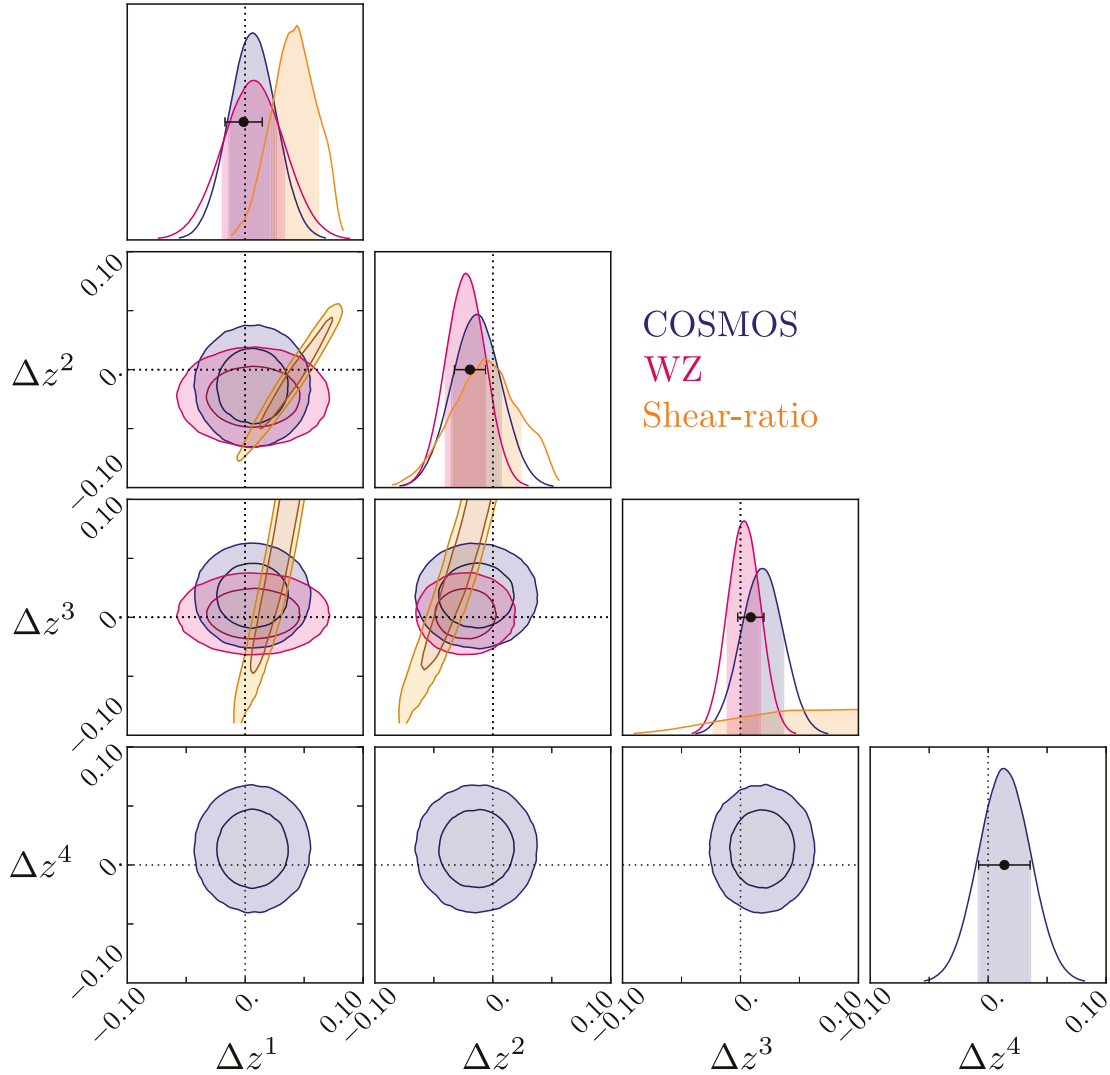
A further check of the accuracy of our  $n^i(z)$  estimation is presented by Prat et al. (2017) using the ratios of lensing shear on the different source bins induced by a common set of lens galaxies. Initially proposed as a cosmological test (Jain & Taylor 2003), the shear ratio is in fact much less sensitive to cosmological parameters than to potential errors in either the calibration of the shear measurement or the determination of the  $n^i(z)$ . We plot in Fig. 7 the constraints on  $\Delta z^i$  inferred by Prat et al. (2017) after marginalization over the estimated errors in shear calibration and assuming a fixed  $\Lambda$  cold dark matter cosmology with  $\Omega_m = 0.3$ . The shear-ratio test is fully consistent with the COSMOS and WZ estimates of  $\Delta z^i$ , though we should keep in mind that this test is also dependent on the validity of the shear calibration and some other assumptions in the analysis, and importantly is covariant with the WZ method, because both methods rely on correlation functions as measured with respect to the same galaxy samples.

## 6 USE FOR COSMOLOGICAL INFERENCE

The final rows of Table 2 provide the prior on errors in the redshift distributions used during inference of cosmological parameters for the DES Y1 data, under the assumption that errors in the  $n^i(z)$  resulting from the photo- $z$  analysis follow equation (1). Determination of redshift distributions is and will continue to be one of the most difficult tasks for obtaining precision cosmology from broad-band imaging surveys such as DES, so it is important to examine the potential impact of assumptions in our analysis choices. Further, we wish to identify areas where our methodology can be improved and thereby increase the precision and accuracy of future cosmological analyses.

### 6.1 Dependence on COSMOS2015 redshifts

First, we base our COSMOS validation on the COSMOS2015 redshift catalogue derived from fitting spectral templates to 30-band fluxes. Our COSMOS validation rests on the assumption that Laigle et al. (2016) have correctly estimated the redshift posteriors of their sources. Overall, redshift biases in the COSMOS2015 redshifts are significant, unrecognized sources of error in our cosmological inferences if they approach or exceed the  $\delta z \approx 0.01$ – $0.02$  range of uncertainty in our  $\Delta z^i$  constraints. More precisely, this bias must



**Figure 7.** Constraints on the shifts  $\Delta z^i$  applied to the METACALIBRATION  $npz(z)$  distributions for the weak lensing source galaxies are plotted for three different validation techniques. Shifts derived from resampling the COSMOS 30-band redshifts are described in this paper, and agree well with those derived (for bins 1–3 only) using angular correlations between the source population and REDMAGIC galaxies (WZ) by Davis et al. (2017) (COSMOS constraints plotted here have been expanded as per Appendix A to include the effects of poorly known correlation between bins). These are also consistent with the weak lensing shear-ratio tests conducted by Prat et al. (2017). The final validation constraints on  $\Delta z^i$  are taken as the combination of the COSMOS and WZ results for each redshift bin (where available), and yield the 68 per cent confidence intervals denoted by the black points and error bars in the one-dimensional marginal plots. The dashed lines at  $\Delta z^i = 0$  indicate no mean shift from the BPZ posteriors – the validation processes yield shifts that are non-zero at  $\approx 1\sigma$  level.

accrue to the portion of the COSMOS2015 catalogue that is bright enough to enter the DES Y1 shear catalogues.

For the subset of their sources with spectroscopic redshifts, Laigle et al. (2016) report that galaxies in the magnitude interval  $22 < i < 23$  have ‘catastrophic’ disagreement between photo- $z$  and spectroscopic  $z$  for only 1.7 per cent (0.6 per cent) for star-forming (quiescent) galaxies (their table 4). This is the magnitude range holding the 50 per cent completeness threshold of the DES Y1 shear catalogues. Brighter bins have lower catastrophic-error rates, and only about 5 per cent of weight in the METACALIBRATION lensing catalogue is provided by galaxies fainter than  $i = 23$ . It would thus be difficult for these catastrophic errors to induce photo- $z$  errors of 0.01 or more.

About 30 per cent of the galaxies used for the COSMOS weak lensing validation have spectroscopic redshifts from the latest 20,000  $I < 22.5$  selected zCOSMOS DATA Release DR3, cov-

ering  $1.7 \text{ deg}^2$  of the COSMOS field to  $z < 1.2$  (Lilly et al. 2009b). We can thus use this subsample as an additional test of this statement. In all redshift bins, the shifts in the mean redshift estimated using this spectroscopic subset are very similar (less than  $1\sigma$  of our error estimate) to the corresponding shifts estimated with photometric redshifts in the full sample. The difference between the 30-band (corrected) photometric mean redshifts and the corresponding spectroscopic redshifts for this subset is also within our error estimates. These tests indicate that the potential (unknown) biases in the 30-band photometric redshifts are smaller than other sources of uncertainty in the mean redshifts used for our WL analysis.

Of greater concern is the potential for bias in the portion of the DES detection regime for which spectroscopic validation of COSMOS2015 photo- $z$ ’s is not possible. Neither we nor Laigle et al. (2016) have direct validation of this subsample, so we are relying on the success of their template-based method and broad

spectral coverage in the spectroscopic regime to extend into the non-spectroscopic regime. Our confidence is boosted, however, by the agreement in  $\Delta z^i$  between the COSMOS validation and the independent WZ validation in bins 1, 2, and 3.

Finally, we note that we have also attempted to validate the photo- $z$  distributions using only the galaxies with spectroscopic redshifts in the COSMOS field, and find consistent, albeit uncompetitive results. The number of galaxies with spectra (20k) is an order of magnitude less than those with reliable photometric redshifts which increases statistical uncertainties, cosmic variance uncertainties and uncertainties from data reweighting.

## 6.2 Insensitivity to $n^i(z)$ shape

Equation (1) assumes that the only errors in the  $n_{\text{pz}}^i(z)$  distributions take the form of a translation of the distribution in redshift. We do not expect that errors in the photo- $z$  distribution actually take this form; rather we assume that the shape of  $n^i(z)$  has little impact on our cosmological inference as long as the mean of the distribution is conserved – and our methodology forces the mean of the  $n^i(z)$  to match that derived from the COSMOS2015 resampling. The validity of this assumption can be tested by assuming that any errors in the shifted-BPZ  $n^i(z)$  from equation (1) are akin to the difference between these distributions and  $n_{\text{COSMOS}}^i(z)$  derived from the resampled COSMOS catalogues during the validation process of Section 4.1. We produce a simulated data vector for the DES Y1 cosmology analysis of DES Collaboration et al. (2017) from a noiseless theoretical prediction using the  $n_{\text{COSMOS}}^i(z)$  distributions. We then fit this data using a model that assumes the shifted BPZ distributions. The best-fitting cosmological parameters depart from those in the input simulation by less than ten per cent of the uncertainty of DES Collaboration et al. (2017). We therefore confirm that the detailed shape of  $n^i(z)$  is not important to the Y1 analysis.

## 6.3 Depth variation

A third assumption in our analysis is that the  $n^i(z)$  are the same for all portions of the DES Y1 catalogue footprint (aside, of course, from the intrinsic density fluctuations that we wish to measure). This is not the case: the failure to apply SLR adjustment to our fluxes in BPZ (Section 3.1.2) means that we have not corrected our Metacal fluxes for Galactic extinction, and therefore have angular variations in survey depth and photo- $z$  assignments. Even without this error, we would have significant depth fluctuations because of variation in the number and quality of exposures on different parts of the survey footprint.

Appendix B provides an approximate quantification of the impact of  $n^i(z)$  inhomogeneities on our measurements of the two-point correlation functions involving the shear catalogue. There we conclude that the few per cent fluctuations in survey depth and colour calibration that exist in our source catalogues should not significantly influence our cosmological inferences, as long as we use the source-weighted mean  $n^i(z)$  over the survey footprint. Both the COSMOS and WZ validation techniques produce source-weighted estimates of  $\Delta z^i$ , as required.

## 7 CONCLUSIONS AND FUTURE PROSPECTS

We have estimated redshift distributions and defined tomographic bins of source galaxies in DES Y1 lensing analyses from photometric redshifts based on their *griz* photometry. While we use

traditional photo- $z$  methods in these steps, we independently determine posterior probability distributions for the mean redshift of each tomographic bin that are then used as priors for subsequent lensing analyses.

The method for determining these priors developed in this paper is to match galaxies with COSMOS2015 30-band photometric redshift estimates to DES Y1 lensing source galaxies, selecting and weighting the former to resemble the latter in their *griz* flux and pre-seeing size measurements. The mean COSMOS2015 photo- $z$  of the former sample is our estimate of the mean redshift of the latter. We determine uncertainties in this estimate, which we find have comparable, dominant contributions from

- (i) sample variance in COSMOS, i.e. the scatter in measured mean redshift calibration due to the limited footprint of the COSMOS field,
- (ii) the influence of morphological parameters such as galaxy size on the lensing source sample selection, and
- (iii) systematic mismatches of the original and matched sample in the algorithm we use.

A significant reduction of the overall uncertainty of the mean redshift priors derived in this work would thus only be possible with considerable additional observations and algorithmic advances.

Subdominant contributions, in descending order, are due to

- (i) errors in photometric calibration of the *griz* data in the COSMOS field and
- (ii) the finite subsample size from the DES Y1 shear catalogues that we use for resampling.

The COSMOS2015 30-band photometric estimates of the mean redshifts, supplemented by consistent measures by means of angular correlation against DES REDMAGIC galaxies in all but the highest redshift bins (Cawthon et al. in preparation; Davis et al. 2017; Gatti et al. 2017), have allowed us to determine the mean redshifts of four bins of WL source galaxies to 68 per cent CL accuracy  $\pm 0.011$ – $0.022$ , independent of the original BPZ redshift estimates used to define the bins and the nominal  $n_{\text{pz}}^i(z)$  distributions. These redshift uncertainties are a highly subdominant contributor to the error budget of the DES Y1 cosmological parameter determinations of DES Collaboration et al. (2017) when marginalizing over the full set of nuisance parameters. Likewise, the methodology of marginalizing over the mean redshift uncertainty only, rather than over the full shape of the  $n^i(z)$ , biases our analyses at less than 10 per cent of their uncertainty. Thus, the methods and approximations herein are sufficient for the Y1 analyses.

DES is currently analysing survey data covering nearly four times the area used in the Y1 analyses of this paper and DES Collaboration et al. (2017), and there are ongoing improvements in depth, calibration, and methodology. Thus, we expect  $>2\times$  reduction in the statistical and systematic uncertainties in future cosmological constraints, compared to the Y1 work. Uncertainties in  $n^i(z)$  will become the dominant source of error in future analyses of DES and other imaging surveys, without substantial improvement in the methodology presented here. We expect that the linear-shift approximation in equation (1) will no longer suffice for quantifying the validation of the  $n^i(z)$ . Significant improvement will be needed in some combination of: spectroscopic and/or multiband photometric validation data; photo- $z$  methodology; redshift range, bias constraints, and statistical errors of WZ measurements; and treatment of survey inhomogeneity. The redshift characterization of broadband imaging surveys is a critical and active area of research, and will remain so in the years to come.

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## APPENDIX A: COMPENSATION FOR UNKNOWN COVARIANCES IN TOMOGRAPHIC ANALYSES

There are four parameters  $\Delta x_i$  in our model for errors in the redshift distribution, which will be used when constraining some parameter(s)  $\pi$  of the cosmological model. While we have produced reliable bounds  $\sigma_i^2$  of the variance of each of these, we have less knowledge of the off-diagonal elements  $r_{ij}\sigma_i\sigma_j$  of the covariance matrix  $C$  of the  $\Delta x_i$  – perhaps we know only that  $|r_{ij}| \leq r$ . We wish to make estimates of  $\pi$  and the uncertainty  $\sigma_\pi$  that we are sure do not underestimate the true error, for any allowed values of the  $r_{ij}$ , in analyses that combine these redshift bins. We show here this can be done by amplifying the diagonal elements of  $C$  by a factor  $f^2$ , while setting the off-diagonal elements to zero (cf. also Zuntz et al. 2017, their appendix D).

We consider a general case where a parameter  $\pi$  depends on a vector  $\mathbf{x}$  of  $N$  elements via a linear relation  $\pi = \mathbf{w}^T \mathbf{x}$  for some unit vector  $\mathbf{w}$ . Without loss of generality, we can assume that the covariance matrix  $C$  of  $\mathbf{x}$  has  $C_{ii} = 1$  and  $C_{ij} = r_{ij}$  for  $i \neq j$ . Since  $C$  is positive definite,  $|r_{ij}| < 1$ . Our task is to seek a value  $f$  such that we can guarantee that our estimate of the error on  $\pi$  exceeds its true uncertainty:

$$\mathbf{w}^T (f^2 I) \mathbf{w} \geq \sigma_\pi^2 = \mathbf{w}^T C \mathbf{w}, \quad (\text{A1})$$

for all unit vectors  $\mathbf{w}$  and any  $r_{ij}$  meeting our criteria. Another way to view this is that we wish to construct a spherical error region in  $\mathbf{x}$  that is at least as large as the ellipsoid defined by  $C$  in every direction.

Clearly, the condition is satisfied if and only if we can guarantee that

$$f^2 \geq \lambda_{\max}, \quad (\text{A2})$$

where  $\lambda_{\max}$  is the largest of the (positive) eigenvalues  $\lambda_i$  of  $C$  ( $i = 1, \dots, N$ ). The eigenvalues are the solutions of a polynomial equation

$$0 = |C - \lambda I| \quad (\text{A3})$$

$$= (1 - \lambda)^N - (1 - \lambda)^{N-2} \sum_{i>j} r_{ij}^2 \quad (\text{A4})$$

$$+ [\text{lower order terms in } (1 - \lambda)] \quad (\text{A5})$$

$$= \lambda^N - N\lambda^{N-1} + \left[ \frac{N(N-1)}{2} - \sum_{i>j} r_{ij}^2 \right] \lambda^{N-2} \quad (\text{A6})$$

$$+ [\text{lower order terms in } \lambda]. \quad (\text{A7})$$

One can see that the roots of this polynomial must satisfy

$$\sum_i \lambda_i = N, \quad (\text{A8})$$

$$\text{Var}(\lambda) = \frac{2}{N} \sum_{i>j} r_{ij}^2 \leq (N-1)r^2. \quad (\text{A9})$$

It is also straightforward to show that the maximum eigenvalue must be within a certain distance of the mean eigenvalue:

$$f^2 = \lambda_{\max} \leq \frac{\sum_i \lambda_i}{N} + \sqrt{(N-1)\text{Var}(\lambda)} \leq 1 + (N-1)r. \quad (\text{A10})$$

If we only know that  $r < 1$ , then we must increase the diagonal elements of the covariance matrix by  $f = \sqrt{N}$ . This applies to the case when all  $N$  values of  $x$  are fully correlated ( $r = 1$ ), and our parameter responds to the mean of  $\mathbf{x}$ .

In the case of our  $\Delta z^i$ , we have  $N = 4$ , and we estimate that correlation coefficients between bins should be modest,  $|r_{ij}| \leq 0.5$  (see Fig. 6). Then, equation (A10) implies that inflating the individual bins' errors by  $f = \sqrt{2.5} \approx 1.6$  will yield a conservative estimate of the impact of redshift uncertainties on any parameter  $\pi$ .

## APPENDIX B: EFFECT OF $n^i(z)$ INHOMOGENEITIES

The DES Y1 analyses assume that the WL source galaxies in bin  $i$  have a redshift distribution  $n^i(z)$  that is independent of sky position  $\theta$ , apart from the intrinsic density fluctuations in the Universe. Our survey is inhomogeneous in exposure time and seeing, however, and furthermore is not properly corrected for Galactic extinction. This induces angular fluctuations both in the overall source density  $n_S$  and in the redshift distribution  $n_S(z)$  of the galaxies in the bin (here dropping the bin index  $i$  for simplicity). For a fixed lens redshift, a fluctuation in source redshift distribution changes the mean inverse critical density. This produces a multiplicative deviation between the measured and the true shear in some angular region, which we will adopt as a rough description of the effect on shear measurements even though the lenses are distributed in redshift:

$$\hat{\gamma}(\theta) = [1 + \epsilon(\theta)] \gamma(\theta). \quad (\text{B1})$$

We can similarly define a deviation of the mean source and lens densities as

$$n_L(\theta) = \bar{n}_L [1 + \delta_L(\theta)], \quad (\text{B2})$$

$$n_S(\theta) = \bar{n}_S [1 + \delta_S(\theta)], \quad (\text{B3})$$

$$\langle \delta_L \rangle = \langle \delta_S \rangle = 0. \quad (\text{B4})$$

The averages above are over angular position  $\theta$  within the footprint. In the DES Y1 analyses, the lenses are REDMAGIC galaxies, which are selected to be volume-limited and hence nominally have  $\delta_L = 0$ .

To ensure that this is true, Elvin-Poole et al. (2017) look for any correlation between  $n_L(\theta)$  and observing conditions. If any such correlations are found, the lenses are reweighted to homogenize the mean density. We can assume therefore that  $\delta_L = 0$  everywhere, i.e. any fluctuations in lens density are much smaller than those in the sources.

Both the determination of the shear response calibration (Zuntz et al. 2017) and the validation of the redshift distribution (in this paper) are produced with per-galaxy weighting, which means that the nominal shear response is calibrated such that

$$\frac{\langle n_S(1 + \epsilon) \rangle}{\langle n_S \rangle} = 1 \quad (\text{B5})$$

$$\Rightarrow \langle (1 + \delta_S)\epsilon \rangle = 0. \quad (\text{B6})$$

We also assume that the source density and depth fluctuations are uncorrelated with the shear signal,  $\langle \delta\gamma \rangle = \langle \epsilon\gamma \rangle = 0$ , since  $\gamma$  is extragalactic in origin, while  $\delta$  and  $\epsilon$  have terrestrial or Galactic causes.

First, we consider the galaxy–galaxy lensing observable (Prat et al. 2017). It is an average of tangential shear of source galaxies about the positions of lens galaxies. Since it is calculated by summing over lens–source pairs, the resultant measurement converges to

$$\langle \hat{\gamma}_t(\theta) \rangle = \frac{\langle n_L n_S(1 + \epsilon)\gamma_t(\theta) \rangle_\theta}{\langle n_L n_S \rangle_\theta} \quad (\text{B7})$$

$$= \langle (1 + \delta_S)(1 + \epsilon) \rangle_\theta \gamma_t(\theta) \quad (\text{B8})$$

$$= \gamma_t(\theta). \quad (\text{B9})$$

Here,  $\theta$  is the separation between lens and source, and the averages are taken over lens–source pairs with separation in some range about  $\theta$ . The last two lines are simplifications that arise from  $\delta_L = 0$  and the vanishing conditions in equations (B4) and (B6) above. The tangential-shear measurement is, therefore, unaffected by survey inhomogeneity, as long as the nominal shear and redshift calibrations are weighted by number of source galaxies, not by area.

The other DES Y1 cosmological observable using the source population is the two-point correlation function of shear  $\xi_\gamma(\theta)$ . The shear  $\gamma$  is a two-component field, and there are two non-trivial correlation functions  $\xi_\pm$ , or equivalently the spin field can be decomposed into  $E$ - and  $B$ -mode components. Guzik & Bernstein (2005) analyse the influence of multiplicative inhomogeneities on the full  $E/B$  field, and demonstrate that such systematic errors shift power between  $E$  and  $B$  modes at a level comparable to the change in the  $E$  mode. Here, we will consider a simplified scalar version of the Guzik & Bernstein (2005) formalism, which we can think of as quantifying the  $E$ -mode errors due to inhomogeneity. If these are small, we do not have to worry about effects on  $B$  modes either.

The calculation of  $\xi_\gamma$  in Troxel et al. (2017) accumulates the shear products of all pairs of source galaxies 1 and 2 separated by angles in a range near  $\theta$ , yielding an estimate

$$\hat{\xi}_\gamma(\theta) = \frac{\langle n_1 n_2 (1 + \epsilon_1)(1 + \epsilon_2) \gamma_1 \gamma_2 \rangle_\theta}{\langle n_1 n_2 \rangle_\theta} \quad (\text{B10})$$

$$= \frac{\langle (1 + \delta_1)(1 + \delta_2)(1 + \epsilon_1)(1 + \epsilon_2) \gamma_1 \gamma_2 \rangle_\theta}{\langle (1 + \delta_1)(1 + \delta_2) \rangle_\theta} \quad (\text{B11})$$

$$\approx \langle \gamma_1 \gamma_2 \rangle_\theta [1 + \langle \delta_1 \delta_2 \rangle_\theta]^{-1} \quad (\text{B12})$$

$$\begin{aligned} & \times \left[ 1 + \langle \delta_1 \delta_2 \rangle_\theta + \langle (1 + \delta_1)\epsilon_1 \rangle_\theta + \langle (1 + \delta_2)\epsilon_2 \rangle_\theta \right. \\ & \left. + \langle \delta_2 \epsilon_1 \rangle_\theta + \langle \delta_1 \epsilon_2 \rangle_\theta + \langle \epsilon_1 \epsilon_2 \rangle_\theta \right] \\ & \approx \xi_\gamma(\theta) [1 + 2\xi_{\delta\epsilon}(\theta) + \xi_\epsilon(\theta)]. \end{aligned} \quad (\text{B13})$$

We have kept terms only to second order in  $\delta$  and  $\epsilon$ . We also exploited the lack of correlation between true shear and the systematic errors. We find, following Guzik & Bernstein (2005), that the systematics lead to a multiplicative error in  $\xi_\gamma(\theta)$  given by the correlation function  $\xi_\epsilon(\theta)$  of the multiplicative systematic; there are additional terms from the cross-correlation  $\xi_{\delta\epsilon}$  of density and depth inhomogeneities, which we expect to be of the same order. Since  $\xi_\epsilon(\theta) \leq \langle \epsilon^2 \rangle$ , the fractional error in  $\xi_\gamma$  is no larger than the *square* of the typical fluctuation in source catalogue density or inverse critical density.

The rms fluctuation in source mean redshift induced by failure to apply the SLR adjustment (Section 3.1.2) is  $\delta z \lesssim 0.01$ . We estimate the effect of variations in survey depth by removing sources above an  $i$ -band MOF magnitude  $m_{\text{lim}}$  from the matched COSMOS sample. The derivative of  $\langle z \rangle$  with respect to  $m_{\text{lim}}$  is below  $0.05 \text{ mag}^{-1}$  in the relevant range of  $m_{\text{lim}}$  for all four source bins. At the variation of depth present in DES Y1 (0.25 mag rms, Drlica-Wagner et al. 2017), this leads to an rms fluctuation in source mean redshift of  $\delta z \lesssim 0.012$ . Jointly, the rms due to both effects, which may be partly correlated, are  $\delta z \lesssim 0.02$  rms.

We expect the source density and inverse critical density (i.e.  $\delta$  and  $\epsilon$ ) to scale no faster than linearly with the mean redshift of the sample, and the lowest redshift bin has  $z \approx 0.3$ , so  $\langle \epsilon^2 \rangle \lesssim (\delta z/z)^2 \approx 0.004$ . Thus, we estimate an overall scaling error of the  $\xi_\gamma$  measurements at roughly this level.

The most accurately measured combination of cosmological parameters in DES Y1 data is  $S_8 = \sigma_8(\Omega_m/0.3)^{0.5}$ , which is determined to a fractional accuracy of  $\approx 3.5$  per cent (DES Collaboration et al. 2017). Since  $\xi_+ \propto S_8^2$ , roughly, its error due to uncorrected Galactic extinction is estimated to be  $\approx 8 \times$  smaller than the uncertainty level in the DES Y1 analyses.

## APPENDIX C: CALIBRATION OF DNF $n^i(z)$

The COSMOS validation procedure of Section 4.1 was repeated for the DNF photo- $z$ 's in the same way as for BPZ, as was the WZ validation. The resultant  $\Delta z^i$  are shown in Table C1 and the  $n^i(z)$  and photo- $z$  precision metrics are plotted in Fig. C1. Note that we do not require agreement between the values for DNF and those for BPZ, because they apply to different binnings of the source galaxies.

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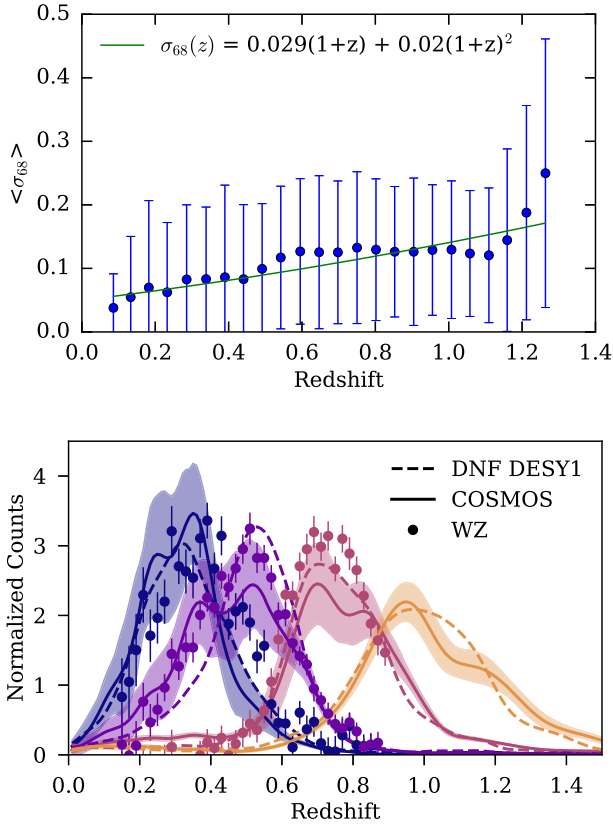
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**Table C1.** Values of and error contributions to photo-z shift parameters of DNF  $n^i(z)$ .

| Value   | Bin 1              | Bin 2              | Bin 3              | Bin 4              |
|---|--------------------|--------------------|--------------------|--------------------|
| $z^{\text{PZ}}$ range                               | 0.20–0.43          | 0.43–0.63          | 0.63–0.90          | 0.90–1.30          |
| COSMOS footprint sampling                           | $\pm 0.0071$       | $\pm 0.0075$       | $\pm 0.0053$       | $\pm 0.0080$       |
| COSMOS limited sample size                          | $\pm 0.0015$       | $\pm 0.0014$       | $\pm 0.0016$       | $\pm 0.0039$       |
| COSMOS photometric calibration errors               | $\pm 0.0023$       | $\pm 0.0029$       | $\pm 0.0046$       | $\pm 0.0045$       |
| COSMOS hidden variables                             | $\pm 0.0030$       | $\pm 0.0080$       | $\pm 0.0090$       | $\pm 0.0030$       |
| COSMOS errors in matching                           | $\pm 0.0069$       | $\pm 0.0069$       | $\pm 0.0069$       | $\pm 0.0069$       |
| COSMOS single-bin $\Delta z^i$ uncertainty          | $\pm 0.011$        | $\pm 0.013$        | $\pm 0.013$        | $\pm 0.013$        |
| METACALIBRATION                                     |                    |                    |                    |                    |
| COSMOS final $\Delta z^i$ , tomographic uncertainty | $-0.024 \pm 0.017$ | $-0.042 \pm 0.021$ | $+0.006 \pm 0.021$ | $+0.038 \pm 0.020$ |
| WZ final $\Delta z^i$                               | $+0.003 \pm 0.014$ | $-0.037 \pm 0.014$ | $+0.005 \pm 0.019$ | –                  |
| Combined final $\Delta z^i$                         | $-0.008 \pm 0.011$ | $-0.039 \pm 0.012$ | $+0.006 \pm 0.014$ | $+0.038 \pm 0.020$ |

**Figure C1.** Top panel: as Fig. 2 showing the average width of the posterior distributions of DNF photometric redshifts. Bottom panel: the  $n^i(z)$  for galaxies with bin assignments and estimated using DNF photo- $z$ 's rather than BPZ. The error bars correspond to the standard deviation of the individual source's  $\sigma_{68}$  around the average. The bottom panel is otherwise equivalent to Fig. 4.<sup>10</sup>Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA<sup>11</sup>Department of Physics, The Ohio State University, Columbus, OH 43210, USA<sup>12</sup>Institut de Física d'Altes Energies (IFAE), The Barcelona Institute of Science and Technology, Campus UAB, E-08193 Bellaterra (Barcelona) Spain<sup>13</sup>Brookhaven National Laboratory, Bldg 510, Upton, NY 11973, USA<sup>14</sup>ARC Centre of Excellence for All-sky Astrophysics (CAASTRO), University of Sydney<sup>15</sup>School of Mathematics and Physics, University of Queensland, Brisbane, QLD 4072, Australia<sup>16</sup>Laboratório Interinstitucional de e-Astronomia - LIneA, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil<sup>17</sup>Observatório Nacional, Rua Gal. José Cristino 77, Rio de Janeiro, RJ - 20921-400, Brazil<sup>18</sup>INAF – Osservatorio Astrofisico di Torino, Pino Torinese, Italy<sup>19</sup>Department of Astronomy, University of Illinois, 1002 W. Green Street, Urbana, IL 61801, USA<sup>20</sup>National Center for Supercomputing Applications, 1205 West Clark St., Urbana, IL 61801, USA<sup>21</sup>Kavli Institute for Cosmological Physics, University of Chicago, Chicago, IL 60637, USA<sup>22</sup>School of Physics and Astronomy, University of Southampton, Southampton, SO17 1BJ, UK<sup>23</sup>Fermi National Accelerator Laboratory, PO Box 500, Batavia, IL 60510, USA<sup>24</sup>Centre for Astrophysics and Supercomputing, Swinburne University of Technology, Victoria 3122, Australia<sup>25</sup>Lawrence Berkeley National Laboratory, 1 Cyclotron Road, Berkeley, CA 94720, USA<sup>26</sup>Australian Astronomical Observatory, North Ryde, NSW 2113, Australia<sup>27</sup>Sydney Institute for Astronomy, School of Physics, A28, The University of Sydney, NSW 2006, Australia<sup>28</sup>Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA<sup>29</sup>The Research School of Astronomy and Astrophysics, Australian National University, ACT 2601, Australia<sup>30</sup>Institute of Cosmology and Gravitation, University of Portsmouth, Portsmouth, PO1 3FX, UK<sup>31</sup>Jodrell Bank Center for Astrophysics, School of Physics and Astronomy, University of Manchester, Oxford Road, Manchester, M13 9PL, UK<sup>32</sup>Department of Physics, University of Arizona, Tucson, AZ 85721, USA<sup>33</sup>Purple Mountain Observatory, Chinese Academy of Sciences, Nanjing, Jiangsu 210008, China<sup>34</sup>Max Planck Institute for Extraterrestrial Physics, Giessenbachstrasse, D-85748 Garching, Germany<sup>35</sup>Cerro Tololo Inter-American Observatory, National Optical Astronomy Observatory, Casilla 603, La Serena, Chile<sup>36</sup>Department of Physics and Electronics, Rhodes University, PO Box 94, Grahamstown 6140, South Africa<sup>37</sup>LSST, 933 North Cherry Avenue, Tucson, AZ 85721, USA<sup>38</sup>CNRS, UMR 7095, Institut d'Astrophysique de Paris, F-75014, Paris, France<sup>39</sup>Institut d'Astrophysique de Paris, Sorbonne Universités, UPMC Univ Paris 06, UMR 7095, F-75014, Paris, France<sup>40</sup>George P. and Cynthia Woods Mitchell Institute for Fundamental Physics and Astronomy, and Department of Physics and Astronomy, Texas A&M University, College Station, TX 77843, USA<sup>41</sup>Department of Physics, IIT Hyderabad, Kandi, Telangana 502285, India

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